IAEA-TECDOC-624

Electricity and the environment

Background papers for a Senior Expert Symposium held in Helsinki, 13–17 May 1991

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ELECTRICITY AND THE ENVIRONMENT
IAEA, VIENNA, 1991
IAEA-TECDOC-624
ISSN 1011-4289

Printed by the IAEA in Austria
September 1991

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FOREWORD

The Senior Expert Symposium on Electricity and the Environment was held from 13 to 17 May 1991, in Helsinki, Finland. It was organized jointly by the Commission of the European Communities (CEC), the Council for Mutual Economic Assistance (CMEA), the International Atomic Energy Agency (IAEA), the International Energy Agency (IEA), the International Institute for Applied Systems Analysis (IIASA), the Nuclear Energy Agency of the OECD (OECD/NEA), the Economic Commission for Europe (ECE), the United Nations Environment Programme (UNEP), the World Bank (IBRD), the World Health Organization (WHO) and the World Meteorological Organization (WMO) and was hosted by the Ministry of Trade and Industry of the Government of Finland.

The objective of the Symposium was to provide a comprehensive assessment of the environmental and health factors as well as the economic factors involved in supplying electricity services, and to suggest a framework within which these issues should be taken into account in making future plans and decisions on electricity production and use. The potential role of different ways of meeting electricity service requirements was also to be analysed, taking into consideration both demand side and supply side options in light of their comparative economic, environmental and health related impacts.

In light of these objectives, International Expert Groups prepared Key Issues Papers on four topics that were selected as the central themes for consideration in the Symposium. A Joint Steering Committee, composed of representatives from the sponsoring organizations and Finland as host country, provided overall guidance to the Symposium and to the work of the four Expert Groups.

Key Issues Paper No. 1, Energy and Electricity Supply and Demand: Implications for the Global Environment, assessed scenarios of future energy requirements, the share of electricity in the end use energy mix in the context of social, environmental and technological development, and the role of electricity in minimizing impacts on the environment.

Key Issues Paper No. 2, Energy Sources and Technologies for Electricity Generation, reviewed the characteristics of different energy sources and technologies for electricity generation, namely, fossil fuels, nuclear energy and renewable energy sources, from the perspectives of resource base, technological capability (including ways of protecting the environment) and economic viability.

Key Issues Paper No. 3, Comparative Environmental and Health Effects of Different Energy Systems for Electricity Generation, made a comparative assessment of the overall environmental and health effects of different energy systems for electricity generation, under normal operating and accident conditions, and covering the entire cycle of energy production, conversion and end use.

Key Issues Paper No. 4, Incorporation of Environmental and Health Impacts into Policy, Planning and Decision Making for the Electricity Sector, examined issues and options for managing the impact of the electricity sector on environment and health, and the framework for incorporating environmental and health impacts into the decision making process for electricity policies and strategies.

In the process of compiling the Key Issues Papers, members of the four Expert Groups prepared the Background Papers contained in this volume, providing greater detail on selected topics that were treated in summary fashion in the Key Issues Papers. The organizations sponsoring the Symposium hope that the wealth of detailed data and information contained in these Background Papers will be a useful contribution to the process of examining comparatively the different options and strategies for meeting future energy and electricity requirements while satisfying the objectives of sustainable development.

EDITORIAL NOTE

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ENERGY AND ELECTRICITY SUPPLY AND DEMAND: *Implications for the Global Environment*

Key Issues Paper No. 1

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DRIVING FACTORS FOR ELECTRICITY DEMAND

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ABSTRACT: Explicative factors of primary energy consumption as well as electricity demand have been widely studied. Most of the results published emphasize the close links between GDP growth rate, demography, prices of energy and energy or electricity demand.

The final goal of this preliminary study aims at formalizing a mathematical tool for long term energy and electricity demand forecasting. On basis of statistical data available for the period 1970-1985, it is tried to establish a formalized relationships between energetic variables and relevant economic and demographic parameters.

1. RATIONALE FOR THE METHOD

1.1 General presentation

In the past, many detailed empirical or analytical analyses on energy demand evolution have been carried out. In most cases it was concluded that energy as well as electricity demand may be explained by few techno-economic determinants. On this background, in this report it is intended to assess correlations between energetic variables and their explicative factors quantitatively on a country by country basis. The econometric approach was the tool used for determining the relationship.

The time frame 1970 to 1985 was chosen to consider also the unusual events that occurred in the energy and electricity sector and thus to illustrate demand variations according to fluctuations of explicative parameters.

The oil shocks and the changes they induce in economic growth rates, give an opportunity to assess the effects of such changes upon energy consumption and electricity demand.

Although the relative roughness of the method prevents from an in depth evaluation of the energetic content of economic growth, it gives a fairly good indication on trends. A country by country analysis was performed to give a quite precise and relevant estimation of links between time series related to energy and electricity on one side and economy and demography on the other. To back carefully mathematical results, a critical review of specific national techno-economic and social conditions was done by analyzing published qualitative and quantitative data.

The study deals with some sixty countries covering OECD (Organization for Economic Co-operation and Development) member states, Centrally Planned Economies in transition, New Industrialized Countries, and the largest LDCs in terms of population and GDP. Some attempts were made to determine global correlations at a regional level, by large zones of the world. However the explicative value of such approach is quite limited, taking into account the wide disparities between countries in each region.

The pre-selection of parameters used to explain for and describe energy and electricity demand evolution was done according to known results from previously published studies.

It should be recognized that such a straightforward approach is unable to fully portray all the macro-economic mechanisms which lead to a given energy situation, for each year and in each country. Despite the simplifying assumptions adopted, the results obtained (see section 3) justify the attempt and indicate trends fairly good.

The selected parameters intend to be representative indicators of economic activity and other factors, having a major impact on energy and electricity requirements. Both economic and energetic variables are highly aggregated.

1.2 Main indicators

The main indicators of economic activities are income, expressed by GDP, and its total and structural development. In order to build a formalized model, the indicators retained in this study are the GDP, expressed in constant prices (US$ of 1980) and the shares of the manufacturing and agricultural industry respectively. Both last parameters describe roughly the economic structure and, with regard to energy and electricity intensities, identify two contrasting economic sectors.

Total population has been used as a first order approximation for population. However, in further detailed demand analyses the appropriate consideration of urban population, particularly in LDCs where some cities alone consume more than three quarters of the electricity provided, is required. Provided reliable statistical data are available, a more sophisticated approach would certainly lead to a better understanding and estimation of electricity demand evolution in some regions of the world.

The adequate consideration of different energy prices and price indicators and their respective changes causes some problems of appraisal in the approach. However, recognizing the major role of oil in world primary energy supply, the international oil market price has been used as the appropriate indicator. For country specific analyses this indicator has been corrected when possible and deemed relevant. For example a correction to international oil price index can be done by incorporating the share of oil in the country's energy supply mix. In cases where the energy prices are fixed according to national policy and time series available, these prices series were adopted for formulating the mathematical structure of the model.

Time series on energy prices for other fossil fuels, coal and gas, indicate clearly the leading role of oil, and justify in most cases to retain only oil prices as explicative for energy consumption evolution.

In addition to the parameters economy, demography and energy prices, the formalized model considers in some cases the temporal trend as well. Such procedure allows to take into account indirect effects of technological progress as well as energy policies which are not easy to quantify.

Moreover, in order to reflect the rigidity of electrical systems and the lead times involved for their adaptation, the electricity consumption of the previous year was retained as explicative, when relevant. The infrastructures of generation and distribution of electricity cannot be adapted rapidly to evolving prices for economic growth, thus a delay between economic changes and the electricity demand evolution they entail could be observed.

1.3 Mathematical tools

The mathematical formulation of the parameters leads to a set of logarithmic equations, one per country, between energy demand, electricity consumption and some of the selected explicative parameters. Assuming a strong proportionality between electricity consumption and population, as indicated by some previous studies, the calculations are carried out on a per capita level. It might be argued that the labor-force provides a better demographic indicator. However, the results of the author's investigations show that the indicator 'global population' is a fairly good first approximation in determining general trends.

For a given country the model retains in most cases no more than three to four parameters, among those described above. This selection is based upon the econometric analysis of numerical time series and upon the results of the correlation between these numerical series.

Nevertheless in addition a more qualitative critical review of the selected parameters and of their economic intensities has been carefully carried out for each country. Although some subjectivity is unavoidable at that stage, such an analysis is needed to assess the quality of the results.

The following equation gives an illustrative example of the form of the models for any country:

$$\text{Log (FELC)} = \alpha \text{ Log (GDPC)} + \beta \text{ log (STMA)} + \tau \text{ Log (PRICE)}$$

Where

FELC	stands for the final electricity consumption per capita (kWh per inhabitant),
GDPC	for the Gross Domestic Product per Capita expressed in constant money (equivalent US$ of 1980),
STMA	for the share of the value added of the manufacturing industry in the overall GDP (in %),
PRI	for the energy price index (international oil price indicator eventually corrected to reflect specific country conditions), and
α,β,τ	estimated parameters.

It should be noted that the study covers electricity demand as well as commercial primary energy consumption. In this context, two models were built for each country. The results given here focus upon electricity demand.

2. DATA BASE, DEFINITION OF ESTIMATED VARIABLES AND EXPLICATIVE PARAMETER

Once the econometric approach has been chosen, the reliability and consistency of the data base is crucial to ensure the validity of the results and conclusions.

2.1 Need for consistency and reliability

Dealing with some sixty countries, including USA as well as Algeria, Thailand, P.R. of China or USSR, and with demographic, economic and energy indicators, the sources of data retained have to be coherent and as exhaustive as possible.

Bearing in mind the needed worldwide consistency, national data base were rejected although they could be, for one given country, more reliable or accurate than international data banks. Nevertheless, when available, statistical data published by national authorities were compared to international sources. In most cases, provided the adjustments are done to take into account definitions, and energy contents equivalents, variations between sources, a fairly good agreement was found.

It was thus chosen to rely upon well assessed international organizations providing long term series of the needed indicators, namely, UN, OECD, and the World Bank.

2.2 Energetic data

Electricity as well as commercial primary energy, consumption is given by OECD/IEA in "World Energy Balances", published in 1989 country by country and year by year from 1970 to 1985. When data are available, mainly for OECD countries, the variable estimated was final electricity consumption which is closely linked to explicative parameters while additional consumptions, pumping, network losses and own consumption of energy sector are more dependant upon technical characteristic of the electricity generation system. This approach leads to consider time series for pumping, losses and own consumption, which are also given by OECD/IEA for its member states.

The energy price indicator is derived from of time series of international oil prices. When country specific indicators are used they are extracted from national statistical data.

2.3 Demographic data

Population figures are available from UN statistical reviews. Besides total population by country some indications related to the repartition between urban and rural areas and to the active work-force are given, however they were not incorporated in the first run of the study, by lack of exhaustivity of the available data.

2.4 Economic data

Economic factors such as GDP volume and structure, are reported by the World Bank in "World Tables", published in 1989. Obviously the estimated value of GDP is highly controversial. The appraisal could be taken as quite accurate as far as OECD countries are concerned, while for LDCs and Centrally Planned Economies countries in transition reliability of gross data collected and of conversion rates adopted are less trivial. Further studies yet underway would allow eventually to reinforce the credibility of the results related to these countries, using more relevant figure of real GDP; however even with the data available, as far as we are concerned more by trends than by precise absolute values, the results could be considered as relevant.

The World Bank gives figures for GDP, on a year by year basis, in current and constant local money. using the GDP series expressed in constant money of 1980 and the exchange rate versus US$ of the same year, we obtained GDP series in 1980 US$, for all countries.

Indicators of structure are limited to manufacturing industries and agriculture shares in GDP formation. It means the implicit assumption that residential and commercial shares of energy and electricity consumption are mainly described through GDP level, indicator of global welfare, and through prices impact.

3. MAIN RESULTS, DRIVING FORCES OF ELECTRICITY DEMAND

The econometric technique, according to the method described above, applied to statistical figures collected in the data bank allows to measure the contribution of each explicative parameter to energy and electricity consumptions.

In each model, selected by its ability to simulate the past evolution of the estimated variable and its plausibility (i.e. relevance of parameters, sign and magnitude of coefficients), the coefficients associated with each explicative parameter give a direct measure of elasticities, as models are built by correlation between logarithmic functions of the variable and parameters.

The relative contribution of each parameter in the variation of electricity consumption gives the weight of the direct impact of this parameter in the global evolution actually observed.

3.1 General trends

In most countries GDP is by far the most important parameter explaining electricity demand evolution. Prices have a lower direct impact, however their indirect impact is already taken into account through GDP growth. As a general rule, energy prices increase tends to lower energy consumption; regarding electricity higher prices of oil lead by substitution to increased demand. Structural effects are important as each transformation from an agricultural economy to a manufacturing dominant economy entails an increasing role of electricity in the energy supply balance.

The interpretation of the numerical results drawn from econometric analysis leads to highlight substantial differences between countries and regions. Nevertheless, some very general trends already illustrated by previously published studies are identified.

Electricity consumption growth rate is higher than primary energy consumption growth rate, as even in the most industrialized and developed countries the electricity has not yet reached its optimum market share of energy supply.

Over the period considered, from 1970 to 1985 in most LDCs electricity consumption growth rate approaches or exceeds 10% per year, while in Eastern Europe and the USSR and also in OECD this growth rate is in average some 5% per year.

It should also be noted that electricity elasticity, defined as the ratio between electricity consumption growth rate and GDP growth rate over the period 1970-1985 is higher than everywhere (with the exception of the U.K. where it is 0.6).

As far as electricity intensity is concerned, a wide range of values is observed in the world in absolute value, from 0.03 kWh/US$80 in Nigeria to 1.08 in Canada for 1970 and from 0.12 to 1.21 in the same countries for 1985. However, in all countries this intensity has increased over the past fifteen years.

3.2 Regional differences

The uniformity of the global trend covers in fact quite different situations in various regions.

For OECD countries the increment of electricity consumption per unit of GDP results mainly from voluntary policies aiming at oil, and others fossil fuels, substitution following the first oil shock, and from structural evolution of the industry towards advanced technologies and processes, highly electricity intensive.

In Eastern Europe and the USSR where electricity intensity was fairly high in 1970, the increase may be attributed to industrial development in sectors where electricity consumption is important such as pulp and paper chemistry, metallurgy. Furthermore, until recent years the level of resources and the basis of the economy of these countries prevented any substantial effort for energy and electricity savings.

The evolution observed in LDCs although similar in trend to that of other regions is more tricky to interpret. In many of these countries the demand is not limited by actual requirements but rather by supply availability.

Once the generating plants and the networks are implemented, consumption raise according to previously existing need. Such a situation leads to a step by step increment of consumption which a rather rough econometric approach fails to describe.

The relationship between electricity intensity and GDP per capita is fairly different from the one between energy intensity and GDP per capita. In fact, according to the data, the saturation level has not yet been reached, as is the case for primary energy. Such an observation leads to expect further increase of electricity demand stimulated by demographic growth, economic development and market penetration at the same time.

4. COMPARISON BETWEEN ELECTRICITY AND PRIMARY ENERGY DEMAND GROWTH RATES

While both electricity consumption and primary energy demand grow with GDP, their rhythms of growth are quite different and the driving forces of this growth are not the same.

4.1 Specific features of electricity

In the case of electricity, although the level of economic development is a main explicative factor, the supply side plays a major role. Electricity has to be generated by large plants and distributed through a network; so the lack of adapted infrastructure prevents any consumption whatever the real need of the population could be. Such features, although more or less implicitly taken in for account by referring to GDP growth rate and structure, are not entirely described by the models above.

Electricity differs from conventional fuels by its highly technical content compared to the flame, and its flexibility. Besides its captive specific usages, the use of the electrical vector is fostered by the development of new processes and devices, aiming at optimizing the global energy systems.

As a result electricity consumption growth is driven by three main factors whose weight is highly differentiated according to country and region.

4.2 Main electricity demand driving forces

The first one, increment of specific uses, is directly associated with GDP growth and concerns mainly LDCs. There most of the needs for lighting, heating, household devices and so on are not met. In countries where electricity consumption is lower than 1 MWh/cap, compared to 5 to 10 or more in Europe, Scandinavia and North America, the main reason for past growth was satisfying elementary needs.

The second one, availability of supply, is crucial mainly in developing regions but important also in other areas such as Eastern Europe. The limitation of demand by supply is illustrated by the electricity path of developing countries.

The third one, development of new processes, for electricity uses, concerns highly industrialized and newly industrializing countries.

The penetration of electricity on new markets has a large impact of global energy systems features and could lead to energy paths very different from country to country. It tends to compensate saturation of demand for specific uses, but the relative weight of these two factors is difficult to appreciate. However it entails that electricity demand growth rate in industrialized countries remains substantially higher than energy consumption growth rate.

The combination of the effects due to these three factors is responsible for the steady growth on electricity consumption observed everywhere during the last decades.

5. CONCLUDING REMARKS

The study of past statistical data over fifteen years makes it possible to establish and interpret the links between political or economical events and electricity demand. The anaLysis and comparison of regional data gives some indications of evolving energy and electricity paths in time. The later industrialization takes place in a country the more efficient it will be in its energy consumption, going directly to advanced technologies including those using electricity.

The results and conclusions from this analysis improve our knowledge on energy and electricity demand relationship with economic growth, particularly when dealing with LDCs. They provide a reasonable basis for putting forward long term energy and electricity demand scenarios.

NOTES ON THE WORLD ENERGY AND ELECTRICITY TO 2050

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ABSTRACT: This paper explores two outline scenarios for the year 2050. The one with a lower environmental impact involves a 'targeted efficiency' future in which per capita energy use in the industrialized countries (OECD + SUEE) is halved by the year 2050, whilst in the developing countries (DEVC) it is doubled. The most important driving forces for the future growth in demand in the DEVC are their increasing population and their need for more services requiring the use of energy and electricity. Less than a doubling in per capita energy would imply unacceptable levels of growth in these services.

In the targeted efficiency future: world commercial energy demand increases by one half, the share arising from the DEVC increases from one quarter to nearly three quarters of the total, and total carbon emissions increase. World electricity demand continues to increase, but the rate of growth becomes much lower than in the past, in response to improved efficiencies and saturation of demand in the industrialized countries, and to improved efficiencies and shortage of investment capital in the DEVC.

1. COMMON FEATURES AND UNCERTAINTIES IN ENERGY FUTURES

A number of common features are likely to be involved in any scenario for world energy in the 21st century. In this section we outline some of these features, and we also indicate other features where there are wide ranging uncertainties.

1.1 Population

The world population in 1990 is about 5.3 billion [1]. It has doubled in the past 40 years, and it is likely to double again by the middle of the 21st century. Even if birth rates were to fall so that the world population becomes stable by 2050, the total would then be about 10.5 billion. This projection is used later to examine its implications for energy futures.

Population growth is greater in developing countries (DEVC) than in the industrialized countries (INDC), which include the OECD group, and the Soviet Union and East Europe (SUEE). In 1960, DEVC formed less than 70% of the total population. Today this share has risen to 77%, and by the year 2050 it will probably be between 85% and 90%. It follows that world energy futures will depend critically on what assumptions are made about future per capita energy demand in developing countries.

1.2 Energy demand

World energy demand (for commercial energy) has increased nearly threefold in the past 30 years [2]. In the 14 years to 1973 it more than doubled, with average growth of 5% pa, but since 1973 its growth has averaged about 2% pa, leading to an increase in world demand of about 40%.

Growth in energy demand has been much greater in developing countries than in the industrialized group, particularly since 1973, [3]. Per capita demand in DEVC has increased by more than 50% since that date, and total demand in this group has more than doubled. In contrast, per capita energy demand in the OECD was almost the same in 1988 as in 1973, though in SUEE it increased significantly, giving an overall per capita increase in the industrial group (INDC).

It is widely accepted that the slow-down in the growth of world energy demand, experienced since 1973, is evidence of a permanent change. In particular, it is a common belief that the average of zero growth in per capita energy demand in the OECD since 1973 reflects a change towards saturation of demand and greater energy efficiency, which will be continued into the future. This belief is not universally accepted, but for some countries it provides the basis for current targets towards reducing the growth in greenhouse gas emissions.

For the longer term future there is less common ground, even for the OECD countries. The CEC reference scenario [4] shows per capita energy demand increasing by nearly 25% between 1987 and 2010, though the CEC's policy oriented 'efficiency' scenarios suggest that there could be a reduction in per capita demand - at least for the European Community. It is often argued that there is an even greater potential for improving energy efficiency in North America. For the SUEE, the present inefficient use of energy accompanies general economic efficiency, and it is reasonable to assume for the longer term future that economic growth could be achieved without a long term increase in per capita energy demand.

It is therefore possible that per capita energy demand in the INDC as a whole may be the same in 2050 as in 1988, namely about 5 toe per capita (1 toe is a tonne of oil equivalent, or 42 GJ). Such a view is probably within the 'plausible range' of many energy analysts. In the next section we shall examine its implications for world energy in a 'targeted growth' scenario (TG). We shall also consider a 'targeted efficiency' scenario (TE) in which the per capita demand in the INDC group is halved by 2050. Such an outcome is probably near the lower end of any range that would be accepted by most energy analysts, and we shall later discuss why such an outcome may seem unlikely.

For the developing countries, there is a difficult dilemma due to the conflict between development, which traditionally has led to greater energy demand, and environmental protection, which seeks to limit the use of fossil fuels. Per capita energy demand for the 4 billion people in the DEVC group averages 0.5 toe, only one tenth of the average for the industrialized countries. A continuation of the average growth in per capita demand during 1973-88 would lead to a six-fold increase by the year 2050. A six-fold increase is most unlikely, and for illustration of a high projection, we shall assume instead a threefold increase in per capita energy use for scenario TG (targeted growth) for the DEVC group. As a low projection TE (targeted efficiency), we shall assume that average per capita energy demand in the DEVC doubles by 2050.

The two scenarios TG and TE will be discussed further in section 2.

1.3 Energy supply

1.3.1 Probable features

Oil: the world will not 'run out of oil' in the next century, but problems with oil will continue to arise as periodic shocks cause demand to adjust within a supply ceiling. This ceiling will probably remain below 4 Gtoe per annum, and it will begin a slow decline in, or before, the middle one-third of the next century. Investment in high-cost oil production will continue to be inhibited by the potential availability of flexible but volatile production from the Middle East - limited by policies, or crises, rather than by resource availability or costs.

The Middle East holds two-thirds of the world's proved reserves of oil. With production averaging 1 Gtoe per annum, these could last for 89 years. With further discoveries, it is reasonable to assume that production could continue near to this level, throughout the 21st century. Production elsewhere currently totals over 2.2 Gtoe, but the R/P ratio is only 21 years. The use of improved production technology in the USSR, and of enhanced production methods elsewhere, coupled with further discoveries could maintain production near to 2 Gtoe for several decades. At that stage, the use of conventional oil could be supplemented by more extensive development of heavy oil deposits, tar sands and shale oil. Resources of unconventional oil are probably much larger than those of conventional oil, and they could help to maintain total world oil production near to 3 Gtoe throughout the 21st century.

Natural gas: proved reserves are equivalent to 100 Gtoe, equal to two-thirds of proved oil reserves. It is likely that ultimate resources of conventional gas are comparable with those of oil, allowing production of 3 Gtoe pa to be maintained throughout most of the 21st century. Current demand is 1.7 Gtoe pa, and it is likely to increase steadily as more natural gas is used to substitute for oil, particularly for electricity generation.

The use of natural gas in competition with oil will help to stabilize world oil demand near to current levels. The longer term transport of gas from production wells to markets will involve three modes:pipelines, LNG, and conversion to liquids. The development of these transport facilities for natural gas will introduce additional flexibility and should help to restrain prices, at least for a decade or two.

The total energy supplied by oil and gas early in the 21st century is expected to be in the region of 6 Gtoe pa, possibly rising 20% above this level before beginning a slow decline after two or three decades.

Hydropower will continue to increase, particularly in developing countries, but its growth will slow as options become more costly and/or more distant from major markets, and as environmental protection is given higher priority. The world total could rise to the equivalent of 1 Gtoe pa, twice its current level, by the year 2050.

Traditional 'non-commercial' fuels (wood etc) will continue to be important in many developing countries. Currently, more than one billion people are almost wholly dependent on these fuels, and, with expected increases in population, this level of dependence is likely to continue.

1.3.2 Uncertain features

The remaining commercial energy supply to meet future world demand will involve coal, nuclear power and new renewable sources (biomass, wind, solar and other). The size of the contribution from these sources is very uncertain. It depends on the evolution of energy demand, future costs, technological change, and social preferences.

From the viewpoints of resources and technology, coal production is the least uncertain. A high level of 8 Gtoe (nearly 4 times current levels) would be feasible by 2050 if there were no environmental constraints. If transportation and trading problems are taken into account, a figure of 5 Gtoe would be more likely.

Nuclear production, currently equivalent to 0.45 Gtoe pa, could increase to 2 or 3 Gtoe by 2050, if nuclear power became a high priority within the next two decades, particularly in the industrialized countries. Alternatively, production could fall quite rapidly after the year 2000, and its contribution to world energy by 2050 could be less than 0.1 Gtoe.

The potential from new renewable sources of energy (biomass, wind, solar, etc) can be illustrated by assuming that their total contribution reaches 50 Mtoe by the year 2000. If subsequent growth was similar to the long-run growth of world coal production (3.5% pa), the total production by 2050 would be less than 0.3 Gtoe. If growth was at double this rate (7% pa), then world production would reach 1.5 Gtoe by 2050. With a higher base assumption of 100 Mtoe in 2000, the last figure would increase to 3 Gtoe. Since the capital investment required for new renewables is likely to be comparable with that for nuclear power, the figure of 3 Gtoe production may not be achievable.

1.4 Electricity

World electricity demand increased at an average rate of 4.5% pa between 1970 and 1988, more than doubling in this period. Primary energy used for generating electricity increased its share of the world total primary energy from 22% in 1970 to 33% in 1988.

Electricity use per capita in 1988 averaged 0.4 MWh in the DEVC group. This may be compared with averages of 7.2 MWh in the OECD and 4.3 MWh in SUEE. Electricity demand is expected to increase more rapidly than energy demand in all major world regions. This increase will be accompanied by improved efficiencies for generating and transmitting electricity.

Investment in electricity supply will remain a problem for many developing countries, where there is a conflict between social needs for low-priced electricity and investment requirements for an adequate return on capital. This will lead to slower growth in the use of electricity in the DEVC, though its growth is likely to remain higher than in the INDC.

2. WORLD ENERGY TO 2050

2.1 Targeted growth TG

More than 4 billion people live in developing countries (DEVC). By the year 2050, on a middle projection (Table I), their population will exceed 9 billion. Their average per capita use of energy is 0.5 toe, only one tenth of the average in the OECD and SUEE, and only one third of the world average.

With 'targeted growth', we assume that the average per capita use of energy in the DEVC increases threefold to 1.5 toe by the year 2050. For the industrialized group, we assume that per capita use remains constant. The outcome for targeted growth is summarized in Table II. World energy demand increases from 7.9 Gtoe in 1988 to more than 20 Gtoe in the year 2050. The average growth in world energy is 1.6% pa, which may be compared with 2.0% pa from 1973 to 1990.

For several decades before 1973, world economic growth was nearly the same as the growth in energy demand. Since 1973, economic growth has been nearly 1% pa above energy growth, but in the OECD since 1979, this 'efficiency gain' has been around 2% pa. If this gain could be continued for the OECD and extended to SUEE, the industrialized countries could achieve an economic growth per capita of 2% pa for the TG projection.

For the DEVC, targeted growth implies 1.8% pa growth in per capita energy demand. It would be in line with past experience for this to be associated with 2% pa economic growth per capita, without any radical change towards greater efficiency in energy use.

The TG projection requires an increase in the world energy supply from 7.9 Gtoe in 1988 to 20.5 Gtoe in the year 2050. An illustrative possibility for energy production to meet this need is given in Table III. Oil and gas provide 6 Gtoe, and hydro provides another 1 Gtoe. With new renewables providing a maximum of 3 Gtoe, this leaves 10.5 Gtoe to be provided by coal and nuclear, currently totalling 2.8 Gtoe. From the viewpoint of global resources and technology, this could be achieved by coal production alone, increasing at about 2.7% pa, well within historical rates of growth. However, such rates of growth in the past have generally been associated mainly with indigenous demand in the major producing countries. Transport costs, particularly for the inland transport of coal, would inhibit its use away from the main producing areas. A maximum of 8 Gtoe for coal production was suggested in section 1, with 2 or 3 Gtoe from nuclear power. This only just meets the residual need, and it indicates that severe energy stresses would result from a TG future. Such a future would also involve a large increase in carbon emissions with consequent risks of climatic change, and a widespread renewal of growth in nuclear power. At the present time, both these outcomes appear to be widely unacceptable, socially and politically.

Table I Population projections to 2050

	Population (billion)	
	1988	2050
OECD	0.77	0.88
SUEE	0.42	0.48
DEVC	3.92	9.16
World	5.11	10.52

Table II Target growth energy demand TG

	Per capita (toe)		Total demand (Gtoe)	
	1988	2050	1988	2050
OECD	5.2	5.2	4.0	4.6
SUEE	4.4	4.4	1.9	2.1
DEVC	0.5	1.5	2.0	13.8
World	1.5	2.0	7.9	20.5

Table III Targeted growth energy supply TG

	World energy (Gtoe)	
	1988	2050
Oil	3.1	3.0
Gas	1.7	3.0
Hydro	0.5	1.0
New renewables	-	3.0
Coal	2.2	8.0
Nuclear	0.4	2.5
World	7.9	20.5

2.2 Targeted efficiency TE

It is unlikely that any target below an average of 1 toe for per capita energy use in developing countries would be acceptable, even under circumstances of extreme environmental concern. With such a low target, equity would demand also that there should be a targeted reduction for the industrialized countries, for example to one half of current levels, giving an average of 2.6 toe in the OECD and 2.2 toe in the SUEE. The targeted efficiency future assumes that this level is achieved by 2050.

With unchanged population projections (Table I), the TE future leads to world energy demand in 2050 equivalent to 12.6 Gtoe, or 60% above the level in 1988 (Table IV).

With a TE future, the preferred fuels (oil and gas) and hydro could provide 7 Gtoe (Table IV). The remaining need of 5.6 Gtoe could be provided entirely by increasing coal production - this might be the least cost option. With such a choice, carbon emissions would be nearly twice the current levels.

Even with reluctance to use coal, it is unlikely that coal production for the TE future in 2050 would be less than 3 Gtoe, since coal is a major resource for future growth in key developing countries, notably China and India. It is also likely to remain an important component for energy production in the USA and the USSR. With plentiful coal supplies, there would be less incentive for developing new renewables, and the option of phasing out nuclear power could be adopted without severe stresses on energy supplies. The stresses in a TE future are more likely to arise from a failure to reach targeted reductions in per capita energy demand on an equitable basis in the industrialized countries, and from unequal growth in developing countries.

3. WORLD ELECTRICITY TO 2050

Electricity consumption per capita currently ranges from an average of 0.4 MWh pa in the DEVC, to 7.2 MWh in the OECD. In a TG future (Table VI), by the year 2050, per capita use in the DEVC has increased more than five-fold to 2.3 MWh, while in the OECD it has less than doubled to 12 MWh pa. The SUEE group doubles its annual per capita use from 4.3 MWh to 8.6 MWh.

In a TE future (Table VII), there is a decrease of 16% in the per capita use of electricity in the OECD between 1988 and 2050. In the SUEE per capita use remains constant, and in the DEVC there is a threefold increase.

The continuing growth of population in the DEVC, coupled with substantial growth in per capita use of electricity, leads to fairly high growth rates for total electricity demand: 4.1% pa in a TG future and 3.5% pa for TE. These are about half the recent historical growth rates for the DEVC, but they are similar to recent growth in the industrialized group.

Table IV Target efficiency energy demand TE

	Per capita (toe)		Total demand (Gtoe)	
	1988	2050	1988	2050
OECD	5.2	2.6	4.0	2.3
SUEE	4.4	2.2	1.9	1.1
DEVC	0.5	1.0	2.0	9.2
World	1.5	1.2	7.9	12.6

Table V Targeted efficiency energy supply TE

	World energy (Gtoe)	
	1988	2050
Oil	3.1	3.0
Gas	1.7	3.0
Hydro	0.5	1.0
New renewables	-	0.5-1.5
Coal	2.2	3.0-5.0
Nuclear	0.4	0.1-1.5
World	7.9	10.6-15.0

Table VI Electricity demand in TG future

	Electricity use per capita (MWh)		Total electricity demand (PWh)	
	1988	2050	1988	2050
OECD	7.2	12.0	5.6	10.5
SUEE	4.3	8.6	1.8	4.1
DEVC	0.4	2.3	1.7	21.1
World	1.8	3.4	9.1	35.7

For the INDC group (OECD and SUEE), our assumptions lead to much lower growth in electricity demand than in the past, and for the OECD in a TE future there is a slight decrease in demand. World electricity growth to 2050 is 2.2% pa for TG, and 1.4% pa for TE (Table VIII). These rates are less than half the average of 4.5% pa experienced during 1970-88.

The data used for electricity demand excludes "own use" in electricity generation and transmission losses. The projections assume that these losses (as percentages) will be reduced by 2050, and that there will be efficiency improvements in generation and transmission. Therefore the primary energy input required for electricity generation increases at a slightly lower rate than electricity demand. However, the primary energy requirement for world electricity generation increases both in absolute terms and as a percentage of total primary energy. This percentage share increases from 33% in 1988 to 43% in 2050. For the INDC it reaches 50% in the latter year (Table IX).

Table VII Electricity demand in TE future

	Electricity use per capita (MWh)		Total electricity demand (PWh)	
	1988	2050	1988	2050
OECD	7.2	6.0	5.6	5.3
SUEE	4.3	4.3	1.8	2.1
DEVC	0.4	1.5	1.7	14.1
World	1.8	2.0	9.1	21.5

Table VIII Electricity demand growth

	Electricity demand % growth per annum		
	1970-1988	1988-2050	
		TG	TE
OECD	3.8	1.0	-0.1
SUEE	4.6	1.4	0.2
DEVC	7.8	4.1	3.5
World	7.9	2.2	1.4

The continuing fairly rapid growth of electricity in the DEVC leads to its increasing importance in world electricity supply. In 1988 the primary input for generating electricity in the DEVC was only 22% of the corresponding world total input for electricity. By 2050 its share rises to 62% for a TG future, and to 68% in a TE future (Table X).

In both the TG and TE futures, there is considerable uncertainty in the allocation of plausible shares of fuel inputs for electricity generation. The richer industrialized group of countries, particularly in the OECD, are likely to 'out-bid' most of the developing countries for convenient or preferred fuels. Because of the large gas resources in the Soviet Union, and the ability of the OECD countries to outbid others for gas imports, natural gas will probably be used disproportionately by the INDC group. With a TG future, this group could also use sufficient coal, hydro and new renewables to meet all its electricity generation requirements, without recourse to nuclear power. This might lead to difficulties in increasing fossil fuel production to meet overall world energy needs in the TG future to 2050.

With the TE future, the problem of fuel allocation arises in a different way. The low demand for energy in the INDC group would result in low prices for fossil fuels in the next few decades. This would reduce the incentive to develop non-fossil alternatives such as nuclear power or new renewables. At a later stage, when energy prices began to increase, these non-fossil sources would begin their growth from a smaller base, and it is likely that a considerable expansion in coal production would be required to meet the growing needs of the developing countries.

Table IX Primary energy shares for electricity generation

	Percentage shares of total primary energy used for electricity generation		
	1973	1988	2050
OECD	25	36	50
SUEE	25	30	50
DEVC	20	28	39
World	24	33	43

Table X Primary energy for electricity generation

	Total primary energy used for electricity generation (Gtoe)			
	1973	1988	2050	
			TG	TE
OECD	0.9	1.4	2.3	1.2
SUEE	0.3	0.6	1.1	0.5
DEVC	0.2	0.6	5.5	3.7
World	1.4	2.6	8.9	5.4

4. AIMS, STRESSES AND GLOBAL WARMING

4.1 Aims

The three objectives, generally related to welfare, that are critical to the demand for services from energy and electricity are:

- economic growth
- affordable energy
- environmental protection

The illustrative energy futures, "targeted growth" (TG) and "targeted efficiency" (TE), imply differing global priorities for these objectives. However, the manner in which such alternative priorities might evolve would be different in each country.

The OECD countries are beginning to accept that climatic change is a long term global problem, which is, to a large extent, a consequence of the way in which they and SUEE (Soviet Union and Eastern Europe) have developed. The SUEE countries have a very large potential for improving their efficiencies of energy use in ways that are economic as well as environmentally beneficial. However, as we have seen above, the longer-term future shows that the growth of energy demand in developing countries is the key to future climatic change.

The conflict of aims is nowhere more difficult than in developing countries. Their population continues to increase. More and better services are needed that require more energy and electricity. Developing countries have more pressing problems to resolve before they can consider cooperation on combating global warming by seeking to reduce emissions of carbon dioxide.

4.2 Stresses

The TG future brings energy stresses that would be particularly severe for those developing countries that do not have indigenous energy resources. Constant per capita energy use in industrialized countries, coupled with their continuing economic growth, implies an ability to pay higher prices for convenient sources of energy. Notably, oil and gas will trade at higher prices. Some developing countries will find their economic growth limited by their ability to pay for energy imports, and by their difficulty in adapting to technologies for using coal, or in developing new renewable sources of energy. Investment capital for electricity production will remain a problem.

The TE future will require a dramatic change in global attitudes to energy use. It is doubtful whether this could result from current concerns alone, arising from scientific analysis, media attention, and international conventions. Climatic shocks of unprecedented magnitude might induce such changes in the industrialized countries - for example, drought and failure of the North American grain harvest for three years running. Such shocks might come after the global climate has begun to change; it would be fortuitous and surprising if they came earlier.

Such serious climatic shocks in one world region would not necessarily provide global incentives. China and India together could produce and use as much coal as the total of today's world consumption. Some countries may expect their climates to improve with global warming; there is significant support for such a view in the USSR. Intense international persuasion would be necessary, and could not be long delayed, if the targeted efficiency energy future was to remain a possibility.

4.3 Global warming

The TG energy future would probably be infeasible unless there is a revived acceptability of nuclear power, leading to a substantial contribution to world energy supply by the year 2050, and a similar contribution from new renewables. If, together, these sources were to provide 5.5 Gtoe pa in 2050, there would remain a need for 8 Gtoe from coal.

The TG future would therefore mean that global carbon emissions from use of fossil fuels would increase from 6 GtC today to 13 GtC in 2050. The result for CO_2 concentrations in the atmosphere would be an increase from 350 ppmv today to more than 500 ppmv in 2050.

The outcome for the TE future is more uncertain since it depends on the options chosen to meet 5.5 Gtoe demand in 2050 from coal, nuclear, or new renewables. Taking account of the availability of coal resources in China and India, it is unlikely that less than 3 Gtoe of this need would be met by coal. The resulting carbon emissions in the year 2050 would be 7.5 GtC, and the CO_2 concentration would be about 450 ppmv.

5. POLICY QUESTIONS

- **Efficiencies**

  In both projections - targeted growth and targeted efficiency - there are strong underlying assumptions that energy efficiencies will be improved. Targeted growth requires the industrial countries (OECD and SUEE) to reduce their energy intensities throughout the period to 2050, at least as fast as the average for the OECD in the 1970s and 1980s. Targeted efficiency requires an additional 1% pa better improvement in energy intensities than with targeted growth.

- **Investment**

  Improved efficiencies of energy and electricity production and use would require the early retirement of capital stock, particularly in the industrialized group of countries. The faster growth of developing countries should generate improved efficiencies provided it is adequately supported by technology transfer. Substantial investment would be required for electricity system improvements, and for all end uses of energy and electricity.

- **Nuclear power and new renewables**

  With targeted growth, it is difficult to see how a plausible world energy balance can be derived without the use of nuclear power. If nuclear power continues to be viewed in many countries as unacceptable as a future option, the need for new renewable energy sources (wind, biomass, solar, other) will become more urgent and improved efficiencies for energy use are essential.

- **Flexibility**

  It is not possible to foresee the full range of needs that require energy and electricity in the future, nor the full range of options for meeting them. Single or simple solutions to meet these needs may be frustrated or aided by changed perceptions, new technologies, or a changing climate. It would seem prudent to seek flexibility by retaining the widest possible variety of options from which to match future energy needs and changing perceptions with acceptable supplies. A decision to close off one option means that its potential contribution must be met by other options. Policy decisions on the development of energy technologies made during the next decade will determine which options will be available to make significant contributions to electricity supply during the next half century.

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WORLD ENERGY HORIZONS 2000-2020

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ABSTRACT: The global energy supply and demand projections for 2000 and 2020 that are presented in this report, are based on a study undertaken by the World Energy Council and released in 1989. The specific feature of this work is achieved commonly by some 30 experts from all over the world, formulating regional projections. This decentralized approach made it possible, in the context of two 'moderate' and 'limited' economic growth scenarios, to draw some reference energy solutions from a 1960-1985 base to both years 2000 and 2020.

Energy supply, demand and exchange projections are presented for five regions and the world as a whole, each projection being split into seven primary energy sources. Combined with economic, demographic and price assumptions, the projections lead to indicators such as: energy intensities, income elasticities, regional autonomies, stresses on energy resources, energy bills, CO_2 emissions, etc.

The projections show a large increase in the world energy demand by some 50 to 75% between 1985 and 2020 with a growing share for developing countries although the average levels of per capita consumption in the South remain critically low. World demand would still mostly be supplied by coal and hydrocarbons with a limited share for nuclear and new renewables and a renewed dominance from Middle East oil exports. Uncertainties mainly focus on financing capabilities, environmental tensions and geopolitical imbalances such as the critical situation of the populated and poorly fueled regions of Africa and South Asia.

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1. METHODOLOGY

The methodology used for analyzing future energy demand and supply is a dominant factor with respect to the findings secured. Therefore, a brief description of the methodology applied by the World Energy Council (WEC) deems necessary in order to understand the uniqueness of the approach.

In contrast with most of other global studies, the WEC survey has not consisted of building a world forecast model but is based on a decentralized consultation of experts. This consultation was basically performed by correspondence, supplemented with joint working sessions.

Under the umbrella of a co-ordination team, more than 30 experts from 18 member committees and 9 international organizations – World Bank, United Nations Economic Commission for Europe, the Commission of the European Communities, the Organization of Petroleum Exporting Countries, etc., have contributed to the study conducting approximately 60 regional expertises.

On the basis of a benchmark period, 1960-1985, and supporting hypotheses, they have drawn up outlooks on energy production, consumption and exchange for the 2000-2020 horizon. The survey distinguished between seven primary energy sources and five world regions. The five regions under study were named NORTH 1 (market economy industrialized countries), NORTH 2 (Eastern Europe), SOUTH 1 (middle income developing countries), ASS+SA (Africa south of the Sahara and South Asia) and CPA (centrally planned asian countries).

The energy system forms part of and interacts with a more complex system that includes economic, environmental (CO_2 effects), demographic and financial elements. Population growth, resource endowments, energy prices, terms of trade, etc. are important parameters that drive the energy system both directly and indirectly, through other interconnected systems.

Nothing is more unknown than the future. Owing to the complex interactions of a multitude of parameters on the local, regional and world level, the future can encompass a great variety of outlooks. The energy forecasts of the WEC have been drawn up as part of two 'moderate (M)' and 'limited (L)' development scenarios, characterized by a certain number of external variables.

Population: World population should increase from 5 billion inhabitants in 1987 to 6 billion in 2000 and should come close 8 billion in the year 2020. It should be observed that between 1985 and 2020, the Third World should account for more than 90% of the total population growth of 3 billion inhabitants.

Economy: Two scenarios have been explored for the economic growth, both basing on the world's average growth of 3%/a for the period 1973-1985. In the moderate growth scenario, world economic growth is assumed to increase to 3.2%/a for the period 1985-2000 and levelling off thereafter at 2.8%/a until 2020. In the limited case, world economic performance will decline to an average of 1.8%/a during 2000-2020, after an intermediate level of 2.4%/a for the period 1985-2000. Economic growth is not equally distributed between the regions of the world. Table I shows the different expectations in economic growth for the NORTH and the SOUTH region.

Oil prices: To take account of uncertainties relating to oil prices, the following price ranges are adopted: in the moderate case US $25-30/bbl for the year 2000 and US $40-50/bbl for the year 2020 respectively; in the limited case US $20-25/bbl for the year 2000 and US $30-35/bbl for the year 2020 respectively (prices in constant values of 1987).

Table I. Average Annual Economic Growth Expected during 1985 and 2020

%/a	1973-1985	1985-2000	2000-2020
NORTH	2.6	2.9 (M) 2.2 (L)	2.3 (M) 1.5 (L)
SOUTH	4.6	4.7 (M) 3.1 (L)	4.2 (M) 2.8 (L)

(M) moderate scenario
(L) limited scenario

It should be recalled that all the supporting hypotheses have been only used to identify the context, the background which the experts have used to formulate their energy forecasts. They have not been used as variables for a predicative model, although in the formulation of their forecasts, the experts may have used both regional models and their own intuition.

2. WORLD ENERGY DEMAND OUTLOOK

World energy consumption could increase from around 8 Gtoe in 1987 (including non-commercial energy sources) to approximately 10 Gtoe in 2000 and eventually 11.5 to 13.5 Gtoe in 2020, depending on the scenarios. This implies in case of the moderate scenario a 75% increase over the 1985 value and still a 50% increase in the limited case.

Although energy consumption is expected to increase, the effectiveness of energy required per economic unit produced, i.e. the energy intensity measured in kgoe per US $ of gross national product (GNP), shows improvements. The intensity had remained generally stable world-wide up to 1973, but decreased markedly during the period 1973-1985 at a pace of 1.1% per year. This trend is expected to continue in the decades until 2020 although at different levels for the moderate and limited case, and the regions. For the world as a whole, a slightly increased rate in energy improvement of 1.2%/a is expected in the moderate case until 2020. Countries of the NORTH and SOUTH region would contribute 1.4%/a and 1.1%/a to the improvement, respectively. The limited case yielded improvements of the intensity of 0.85%/a on average during 1985-2020; the NORTH region contributing 1.1%/a and the SOUTH region 0.4%/a.

Growth in energy consumption will be pronounced in the SOUTH region. The share of the SOUTH region in world energy consumption will increase from 24% in 1973 to 43% in 2020. After the year 2000, the SOUTH will become responsible for most of the increase in the world energy consumption. Already between 1985 and 2000, the SOUTH will take up more than 50% of the increase in energy consumption. For the period 2000-2020, this trend is enforced in the moderate case to about 66% of the world energy consumption. The limited case shows a 76% share of the SOUTH in the world consumption increment.

Energy consumption per capita is expected to increase in both regions, NORTH and SOUTH. Whereas slow population growth and even slower energy growth will be the driving forces in industrialized countries for the increase, it will be high population growth and even higher energy growth in developing countries. Industrialized countries consumption per capita could continue to increase from 4.25 toe in 1985 to 4.5-5.2 toe in 2020 depending on the scenario. The population growth in the Third World will absorb most of the steady increase in energy consumption. Therefore, per capita energy consumption in the Third World will experience a difficult take-off and will, in any event, be less than 1 toe in 2020. Nevertheless, in 2020 on the world level, in both cases, the moderate and limited scenario, per capita energy consumption will practically remain at the level experienced throughout 1973-1985, i.e. about 1.6 toe per capita (1.73 toe per capita in the moderate and 1.48 toe per capita in the limited case respectively).

Table II shows the primary energy demand forecasts for the years 2000 and 2020.

Table II. Primary Energy Demand in 2000 and 2020

	1985		2000				2020			
			M		L		M		L	
	Mtoe	toe/cap	Mtoe	toe/cap	Mtoe	toe/cap	Mtoe	toe/cap	Mtoe	toe/cap
Market economy	3610	4.17	4350	4.57	4025	4.23	4840	4.71	4130	4.02
Centrally planned economy	1740	4.42	2265	5.27	2150	5.00	2885	6.20	2520	5.42
SUBTOTAL NORTH	5350	4.25	6615	4.78	6175	4.47	7725	5.17	6650	4.45
Middle income developing countries	1030	1.01	1635	1.18	1505	1.08	2530	1.37	2215	1.20
Third World in transition	505	0.36	790	0.40	740	0.37	1300	0.46	1095	0.39
Centrally planned Asian countries	785	0.68	1220	0.88	1110	0.80	1970	1.17	1600	0.95
SUBTOTAL SOUTH	2320	0.65	3645	0.77	3355	0.70	5800	0.92	4910	0.78
WORLD	7670	1.59	10260	1.67	9530	1.55	13525	1.73	11560	1.48

3. WORLD ENERGY SUPPLY

Energy consumption in 2020 will be covered by a wide range of energy sources. Coal will regain its market dominance and, together with crude oil, will share about 55% of the total supply market (moderate and limited scenario). Natural gas supply will progress markedly in absolute term, whereas its relative contribution would remain approximately at its 1985 level, which was around 18%. Nuclear energy will experience a break through in the period until 2020. Its relative contribution to the energy supply pattern will double in the moderate scenario experiencing a share of about 8% and slightly less than that in the limited scenario (7%). The share of hydropower in the moderate as well as in the limited scenario will reach about 7.5% implying a 30% growth of its respective value in 1985 (5.9%). The period 1985-2020 will show an emergence of new energy sources and a slow down of non-commercial energy sources. Despite their large contribution to the energy supply mix in absolute terms, the relative contribution of non commercial energy sources will decline in the moderate scenario to less than 8% in 2020 compared to around 11% in 1985; for the limited scenario, the share is expected to remain at its 1985 level. New sources are foreseen to enter the energy supply market at a large scale only during the second decade of next century, levelling in 2020 at 2.7% for the moderate and at 1.5% for the limited case.

The world trend in energy supplies is the result of the combination of regional trends. The situation in INDUSTRIALIZED COUNTRIES shows a certain recovery of oil demand up to 2000, reversing the trend observed during 1973-1985; however, this trend slightly curbs downwards after the year 2000. Owing to the introduction of improved technologies for 'clean' coal combustion, coal will increase its share in the market. Natural gas supplies will experience a steady growth up to the year 2000 with a smooth leveling off in the periods thereafter. The contribution of nuclear power will increase significantly owing partly to the response of the climate concern. The already highly exploited potential of hydropower will limit its further extension. Non-commercial energy sources will keep their level in absolute terms but will decline significantly in their relative shares. New energy sources will gain ground. Their share in the energy supply mix in 2020 will be between 1.2 and 2.2% depending on the scenario.

The energy supply scenario for the SOUTH, the developing world, is quite different. Non-commercial energy, the first energy source in 1985, should stabilize to the benefit of commercial energy sources, but should remain in third position in 2020, not having reached a ceiling on the quantities consumed. Among the commercial energy sources, coal and oil show remarkable progress, whereas hydropower and gas follow a regular pattern. The growth of nuclear and new energy sources remains limited. The supply mix is shown in Table III.

The events in 1973 and 1980 favour a closer look at the availability of crude oil. In general, it is expected that, stimulated by the growth of needs, the world oil production will increase considerably: from 2.8 Gtoe in 1985 to 3.4-3.6 Gtoe in 2000 and 3.4-4.2 Gtoe in 2020. But the regional contribution of crude oil to the world total will experience some changes. The reward of the Western countries' diversification effort (NORTH 1) showed an increase in the production of crude oil. But the quasi-impossibility of sustaining this effort in the long term emerges as well. In parallel, NORTH 2 (Eastern countries) should loose ground as well and could become a net importer of energy by the year 2020. The Third World would achieve general progress, especially through the regained hegemony of SOUTH 1 (which includes 90% of the OPEC output and other large exporters of the South), with a distribution placing industrialized countries in 2020 in an even worse position than in 1973. The expected regional trend in oil production is given for the moderate scenario in Fig. 1.

As far as resources are concerned, few global tensions will emerge up to the year 2020 in aggregate coal, gas and uranium supplies. By contrast, at the level estimated at the start of 1988, some tensions could be perceptible on the cheapest oil supplies in the period 2010-2015. Table IV throws some light on the expected resource stresses.

Table III. Primary Energy Supplies in 1985 and 2020

	Coal	Oil	Natural Gas	Hydro.	Nuclear	New Energies	Non-commer.	TOTAL
Market economy	913	1357	718	262	264	10	89	3613
Centrally planned economy	602	480	515	50	48	1	43	1739
SUBTOTAL NORTH	1515	1837	1233	312	312	11	132	5352
Middle income developing countries	59	493	123	80	11	8	255	1029
Third World in transition	94	74	20	25	1		292	506
Centrally planned Asian countries	448	93	12	28			201	782
SUBTOTAL SOUTH	601	660	155	133	12	8	748	2317
WORLD	2116	2497	1388	445	324	19	880	7669

2020 Scenario 'M'

	Coal	Oil	Natural Gas	Hydro.	Nuclear	New Energies	Non-commer.	TOTAL
Market economy	1385	1405	720	400	700	140	90	4840
Centrally planned economy	929	565	1010	80	230	35	35	2884
SUBTOTAL NORTH	2314	1970	1730	480	930	175	125	7724
Middle income developing countries	200	980	450	355	128	110	305	2528
Third World in transition	315	298	120	110	25	45	390	1303
Centrally planned Asian countries	1222	295	55	98	30	35	235	1970
SUBTOTAL SOUTH	1737	1573	625	563	183	190	930	5801
WORLD	4051	3543	2355	1043	1113	365	1055	13525

Table III. continued

2020 Scenario 'L'

	Coal	Oil	Natural Gas	Hydro.	Nuclear	New Energies	Non-commer.	TOTAL
Market economy	1165	1260	635	360	540	70	100	4130
Centrally planned economy	760	540	895	70	180	15	60	2520
SUBTOTAL NORTH	1925	1800	1530	430	720	85	160	6650
Middle income developing countries	150	945	350	266	70	60	375	2216
Third World in transition	190	229	80	73	15	15	495	1097
Centrally planned Asian countries	973	203	38	79	15	10	280	1598
SUBTOTAL SOUTH	1313	1377	468	418	100	85	1150	4911
WORLD	3238	3177	1998	848	820	170	1310	11561

Table IV. Stresses on World Energy Reserves

Gtoe	Cumulative production 1985-2020 Scenario M	Cumulative production 1985-2020 Scenario L	Proven reserves by 1/1/85	Proven reserves by 1/1/88
Coal	106	93	651	
Oil	126	118	97	122
Gas	71	63	74	93
Uranium	25	20	34	

4. INTER-REGIONAL EXCHANGES

The growth in energy supply will have a strong impact on the international energy trade pattern. The exchanges between the five regions, NORTH 1 and 2, SOUTH 1, ASS+SA and CPA, had declined from 1.4 billion toe to 0.9 billion toe during the period 1973-1985 by reason of the decrease in oil consumption. Upward recovery is clearly emerging. Inter-regional trade should stabilize around 1.2 Gtoe in the moderate scenario and between 1 and 1.1. Gtoe in the limited scenario.

Translating the terms of inter-regional energy trade into an energy bill between the main two regions concerned, SOUTH 1 for export and NORTH 1 for import, shows that the bills are expected to rise reaching in the year 2020 a level similar to those of 1980 (after the second oil shock). The expected development of the energy bills in both regions, SOUTH 1 and NORTH 1, is given in Fig. 2.

5. CO_2 EMISSIONS

A general trend towards the diversification of regional responsibility in pollutant emission is observed. In the long run, Eastern countries and the Third World should step into the NORTH 1 region's shoes.

Total CO_2 emission due to energy consumption should increase by 70% in volume by 2020 in 'M' and by 40% in 'L', concentrations themselves increasing by 10 to 15% from the 1985 level.

The intensity in terms of tonnes of CO_2 per US \$ of GNP tends to slow down, reflecting the progressive decoupling of the world economy growth from the energy consumption growth and the onset of its reduction in fossil fuels.

6. CONCLUSIONS

Major issues emerge from the outcome of the WEC survey whose sole purpose is to outline plausible benchmark trajectories and not to predict the future.

- Issues related to energy demand

  The main questions on the growth rate of energy demand center around population and economic growth. Especially the rate of population growth in Third World countries and the ageing of the population in industrialized countries are important but uncertain driving forces in energy demand.

  Another uncertainty is linked to the intensity of energy use. The survey pre-supposes a follow up of energy gains in the North, at the pace recorded in 1973-1985 and the growth at a very near pace in the South. This assumption is rather optimistic, particularly in light of the disturbing trend since the counter oil shock in 1986. The reality of the increase in Third World countries remains. The chronic weakness of consumption levels per inhabitant poses the problem of possibly faster energy growth than that envisaged in the survey.

- Issues related to energy supply

  Stresses on energy resources are not foreseen in the period until 2020. However, towards the end of the survey period, new tension factors could appear and act earlier on prices, especially in the field of hydrocarbons. As regards renewable energy sources, the more realistic assessment of their pace of penetration is reflected by much slower progress. Presently weak prices of crude oil and high investment cost for new energy technologies might be the near term hinderance for a faster market penetration.

  An equally important problem relates to financing of the energy production and exploration facilities. At least in the short term, indebtness is a brake to investment in many Third World countries and major projects, which are very capital intensive, are thus penalized.

Environmental problems remain, relating at various degrees to practically all energy sources:

Nuclear power whose problems are concentrated on the risks of accident, management of long life waste and the opening of new sites (the difficulty attaches similarly to hydropower).

Massive and disorderly use of non-commercial sources contributes to serious problems of deforestation and desertification.

Fossil fuels, which cause local pollution problems of acid rain and sulphur and nitrogen oxides, and more generally, contribute to the greenhouse effect, are the major source of concern.

- Issues of geopolitical uncertainties

Energy supply is concentrated in a few regions:

- 80% of the coal reserves and resources are in the hands of three countries, China, the USSR and the USA;
- most of the nuclear industry is in developed countries;
- gas reserves are, in the long run, concentrated in the USSR and the Middle East, and
- oil reserves are concentrated in SOUTH 1 (OPEC countries) plus all other main Third World exporters.

In this context, one should keep in mind that the oil production scenarios adopted in the WEC survey are probably optimistic for the NORTH 1 and the NORTH 2 regions, the more so as Eastern Europe will doubtless become a net importer in the long run. The strategical importance of the probable recovery of the hegemony enjoyed by Third World exporting countries should thus be measured in a context which is coming gradually closer to that which preceded the 1973 oil shock: rise in American and West European imports, oil prices at a rather low level, relaxation in energy saving efforts and oil substitution policies.

The energy system itself may experience thorough changes.

Diversification to smaller and modular operation schemes, upgrading existing schemes and improving management efficiency is on the agenda in both industrialized countries and the Third World.

Are we really preparing for the future?

There is a striking contrast between the apparent abundance on the energy market today and the prospects of tensions and long term price rises.

The magnitude of international co-operation is at stake.

The region comprising Sub-Saharan Africa and South Asia alone could number 2.8 billion inhabitants in 2020 (i.e. one out of three persons populating the planet at the time). Each one of them would consume no more than a toe of energy annually at that date (i.e. ten times less than the average inhabitant of the North to-day) to cover all its industrial, transportation, commercial and domestic needs; of which 30 to 40% will still be supplied in the form of scarce fuelwood and poor animal and vegetable residues. Can such a critical situation be left unattended? This is a real risk for peace altogether, at the same time, a real chance for solidarity.

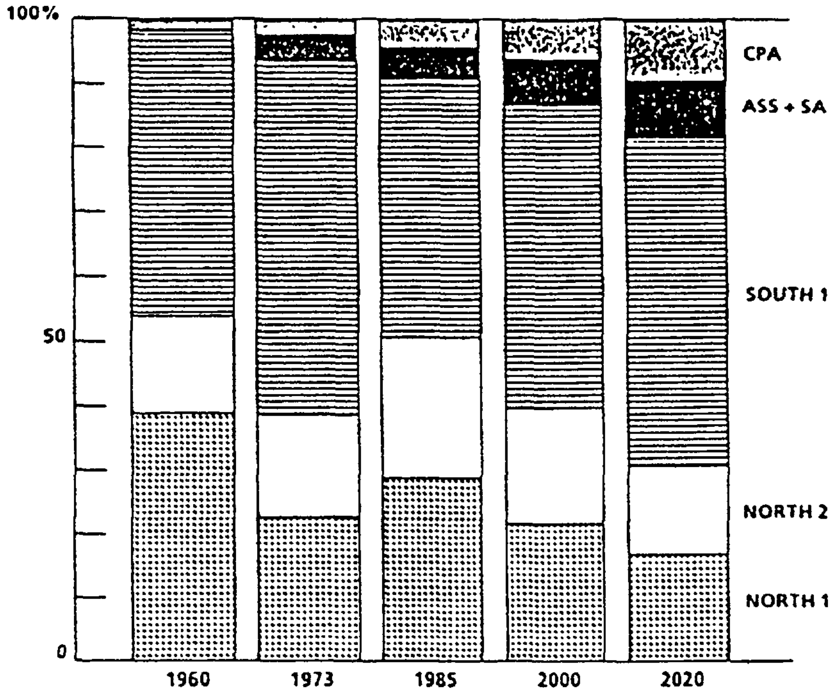

Fig. 1 Structure of World Oil Production, 1960-2020 (Scenario 'M')

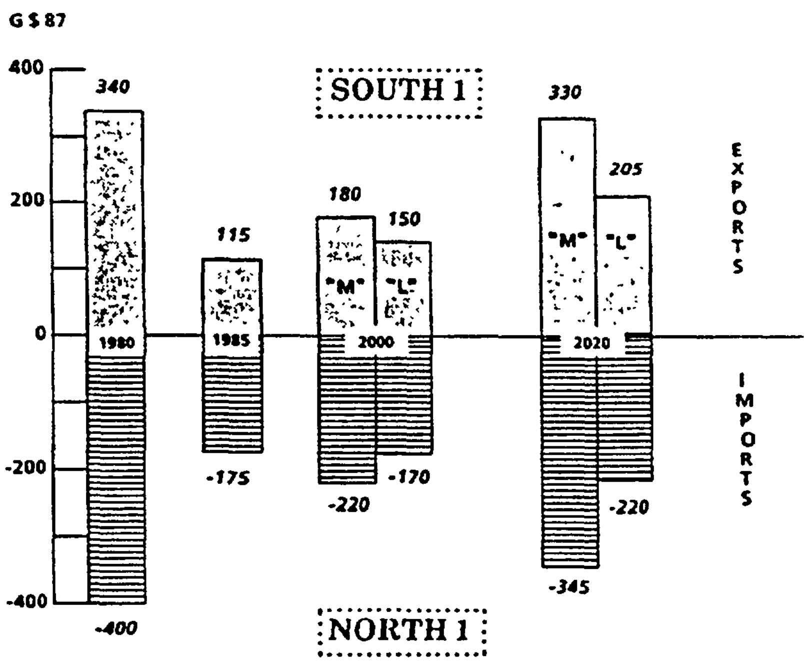

Fig. 2 Development of the Energy Bills in NORTH 1 and SOUTH 1, 1980-2020

POTENTIALS FOR ELECTRICITY SAVINGS IN WESTERN EUROPE

- Illustrated by the Danish Brundtland Energy Plan -

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ABSTRACT: Several Western European countries have developed Brundtland energy plans with the main goal of reducing carbon dioxide (CO_2) emissions. Denmark launched the Energy 2000 study last year showing that it is possible to reduce carbon dioxide emissions considerably. Gross energy consumption can be reduced significantly, but what concerns electricity consumption, it will cause a slow down in the growth rate, only.

Other Western European countries have developed or are developing similar energy/environmental plans aiming at reducing emissions of carbon dioxide, particularly. Following the agreement last year the European Communities have committed themselves to stabilize carbon dioxide emissions by the year 2000 at the 1990 level.

Thus, several attempts are being made to reduce carbon dioxide emissions. Though for most countries it will probably be difficult to reduce electricity consumption proportionally. Due to strong substitution towards electricity use in most Western countries, even severe savings attempts will most probably only reduce growth rates. In spite of this, the Danish case shows that it will be possible to reduce emissions of carbon dioxide considerably.

1. DEVELOPMENT OF ELECTRICITY CONSUMPTION IN WESTERN EUROPE

The development of electricity consumption in OECD-Europe is shown in Fig. 1. With a few exceptions the increase in electricity consumption has followed a trend – in average within the past ten years electricity consumption has increased by 3.1% p.a.. But this increase is unevenly distributed among the countries in Western Europe. As seen from Table I growth rates range from 0.7% p.a. in United Kingdom to 6.0% p.a. in France. The EEC has grown with 2.8% p.a. as a ten years average, and North America with 2.4% p.a.

Table I 10 year average growth in electricity consumption, % p.a.

	Average growth (%/p.a.)
OECD-Europe	3.1
Austria	3.0
Belgium	3.0
Denmark	2.9
France	6.0
Germany	2.2
Italy	1.9
Spain	3.6
Sweden	5.0
United Kingdom	0.7
OECD - total	2.7
EEC	2.8
North America	2.4

2. ENERGY 2000 - THE DANISH BRUNDTLAND ENERGY PLAN

2.1. Background

At the beginning of 1989 the Danish Ministry of Energy initiated work on the Danish Brundtland Energy Plan. The plan was completed in the spring 1990 and submitted to the Danish parliament in April this year.

The Brundtland Energy Plan was naturally inspired by the report of the World Commission on Environment and Development: Our Common Future (the Brundtland Report), which deals with the problems of how to achieve sustainable development. At the end of 1988 the Danish government launched a catalogue of ideas aimed at working towards sustainable development. Following the Brundtland report a sustainable development will imply a 50% reduction in our use of energy at least. The effort on the Brundtland Energy Plan centers on how these ideas can be applied to actual problems in energy and environment.

Five working groups were set up to carry out the work and these groups dealt with the following topics:

- space heating and electrical appliances,
- industrial energy consumption,
- technologies for producing power and heat,

- biomass and local resources, and
- energy and environmental systems.

The first four groups were given the specific task of collecting data on technologies, potentials for energy savings, etc., and how these could develop with time. Each of these working groups submitted comprehensive reports on their respective areas to contribute to the final report on the Brundtland Energy Plan. The final group was responsible for coordinating data collection and applying these data in different scenarios set up by the newly constructed Brundtland scenario model. A brief review of the main characteristics of the model will be given below.

2.2. The Brundtland scenario model - BRUS

The Brundtland Energy Plan has a long time horizon, and the calculational tools that are developed have to deal with energy, the environment, and the national economy in an integrated way:

The main characteristics of the Brundtland scenario model can be summed up as follows:

- long-term simulation model, looking ahead to year 2030,
- split into different sectors of demand and supply, although these sectors are integrated to give a comprehensive tool,
- energy demand and the development of energy production capacity are driven from the demand side,
- possible to choose different savings options for insulation, appliances, and processes,
- possible to choose from a large number of conversion technologies, ranging from individual oil burners to wind turbines and large-scale coal-gasification plants.

The main results of the model are gross energy consumptions split into different fuels, emissions of CO_2, SO_2 and NO_x, and, finally, the economic consequences of the chosen system set-up.

The structure of the model is illustrated in Fig. 2.

Energy consumption for transport is not treated explicitly in the model. The shown module in Fig. 2 may be regarded as a dummy. The main reason for this is that transport is the responsibility of the Ministry of Transportation rather than the Ministry of Energy. In due course the results of the Brundtland work carried out in the Ministry of Transportation will however be included in the Brundtland scenario model.

As mentioned above, the model is an integrated tool for the whole energy system and substantial changes can be introduced in one module without generating the need for changes elsewhere in the model. For example the demand for energy can be halved without changing the supply system and the model can still generate reasonable results. In the case of diminishing energy demand it still might be relevant to change the supply structure.

2.3. Input data for the model analyses

A large number of input data was generated by the working groups to be used in the model analyses. Among these data were estimations of savings potentials and the related costs of obtaining these potentials. In the following a few examples will be given.

Savings potentials for household appliances and the related extra costs are given in Table II and III, below. As seen from Table II it is estimated that more than 80% savings can be obtained for the most efficient appliance in year 2015, compared with the average of 1988. The extra costs are stated in Table III. The most efficient appliance on the market today has no extra costs compared to the average, while it is expected that the future development and production of low-energy appliances will have some additional costs.

Table II Estimated development in electricity consumption for the most efficient appliances (kWh/year)[1]

Appliance	Average consumption in 1988 (kWh)	Most efficient appliance (kWh)		
		in 1988	in 2000	in 2015
Washing machine	400	255 (36)	155 (61)	80 (80)
Cloth dryer	520	310 (40)	180 (65)	150 (71)
Dish washer	500	300 (40)	165 (67)	130 (74)
Refrigerator	350	150 (57)	90 (74)	50 (86)
Freezer	500	330 (34)	100 (80)	80 (84)
Combined	600	460 (23)	150 (75)	130 (78)
Oven	150	105 (30)	75 (50)	60 (60)
Cooling device	550	380 (31)	220 (60)	200 (64)
Water heater	2400	2100 (13)	2000 (17)	2000 (17)
Lighting	650	170 (74)	150 (77)	120 (82)
Water bed	1000	750 (25)	0 (100)	0 (100)

Note. [1] Figures in parenteses show the percentual savings compared to average consumption in 1988

Similar input data were generated for the public and tertiary sector, and the industrial sector. For the public sector the main results are shown in Table IV and V. The savings potentials are estimated in relation to a reference case (Table IV), and the related costs are shown in Table V according to the 3 thirds of realized potentials. For example to realize the 1st third of savings potentials for lighting the consumer will not only save energy, but will reduce the costs of lighting by 10 øre/kWh saved (excluding the gains from energy savings).

Finally, the estimated electricity savings in processing are shown in Table VI. Investments to obtain electricity savings are estimated to be about 1/4 million Dkr. (US $42,000) per saved TJ of gross energy consumption.

Table III Extra costs for obtaining electricity savings (kr./appliance) (1 US$ = 6.0 DKK)

Appliance	Potential in 1988 (kr./app.)	Potential in 2000 (kr./app.)	Potential in 2015 (kr./app.)
Washing machine	0	0	0
Cloth dryer	0	400	50
Dish washer	0	300	0
Refrigerator	0	150	100
Freezer	0	400	150
Combined	0	700	100
Oven	0	200	100
Cooling device	0	0	0
Water heater	0	0	0
Lighting	20	0	0
Water bed	0	0	0

Table IV Reference development in electricity consumption (GWh) and estimated savings potentials (% of reference) in the public sector

Year	Reference development (GWh)				Savings potentials (%)		
	1988	2000	2015	2030	1988-	2000-	2015
Lighting	1056	1061	920	803	52	58	60
Ventilation	760	924	1139	1297	48	57	62
Heating	277	327	354	428	24	33	39
Electronics	174	336	417	531	31	49	75
Pumping	633	808	901	983	52	56	59
Misc.	565	907	1180	1637	29	26	30
Total	3463	4412	4911	5678	44	48	53

Table V Average additional costs for obtaining savings potentials (øre/kWh saved) (1 DKK = 100 øre, 1 US$ = 6.0 DKK)

	1st third of potential	2nd third of potential	3th third of potential
Lighting	- 10	0	15
Ventilation	0	15	35
Heating	0	10	25
Electronics	- 10	0	15
Pumping	0	10	25
Misc.	0	5	20

Table VI Estimated electricity savings in processing

Process	Savings of electricity consumption (%)												
	% of cons. in 1988	Total[1]				Due to information campaigns etc.				Due to non-viable investments			
		1990	2000	2015	2030	1990	2000	2015	2030	1990	2000	2015	2030
Lighting	10	20	55	60	65	15	25	25	25	0	15	15	15
Ventilation	14	20	55	60	65	15	25	25	25	0	15	15	15
Use of process air	8	20	45	50	55	20	20	20	20	0	20	20	20
Cooling	7	20	40	55	60	15	15	15	15	0	20	30	30
Pumping	12	20	50	55	60	15	15	15	15	0	20	20	20
Misc	32	5	20	25	40	5	5	5	5	0	10	10	10
Process heat	4	5	20	25	25	5	5	5	5	0	10	10	10
Melting	10	4	25	27	30	4	4	4	4	0	20	20	20
	3	11	33	38	43	5	7	7	7	0	11	11	11

Note [1] The total includes savings due to campaigns and non-viable investments, and savings obtained through a continuation of historical trends.

2.4. Partial scenarios

As a starting point for the model analyses a reference case was defined:

- the reference case is a continuation of the pre-Brundtland situation, that is the development of the Danish energy system is based on high-efficient coal-fired power plants, not taking into account any restrictions on carbon dioxide emissions, but highly economic efficient on the supply side.

In comparison to this reference a large number of partial model analyses concerning energy savings and different technology configurations were performed using the input data as stated in Table II-VI above. For the demand side these partial analyses included a realization of the savings potentials for:

- energy use in processing [6][1]
- electricity use in households and the tertiary sector [7]
- heating in existing buildings [8]
- heating in new buildings [9]
- energy demand for all consumption sectors [5].

or the supply side different technology configurations were analyzed:

- maximum connection to the district heating grid [10]
- maximum use of combined heat and power (CHP) [11]
- maximum use of CHP and intensive use of biomass [12]

[1] Numbers in brackets relate to the scenarios in Fig 3.

- maximum use of natural gas for domestic heating and processing purposes [13]
- maximum use of renewable energy technologies, i.e. wind-energy, solar etc. [14]
- introduction of high efficient supply technologies for CHP, as combined-cycle plants, coal-gasification plants and fuel cells [15].

The results of these partial analyses are shown in Fig. 3.

Fig. 3 shows the relations in the year 2030 between annual carbon dioxide emissions and total annual energy systems costs, including levelized capital costs and the costs of fuels and operation and maintenance. At Fig. 3 scenarios situated below the reference case (point 1) are preferable what concerns carbon dioxide emissions, and scenarios to the left of the reference are preferable what concerns economy.

Today, the Danish energy system emits about 48 mill. t/year of carbon dioxide. To achieve the targets of the Brundtland report, however, partial actions such as energy savings are not enough. To reduce the emission of CO_2 by 50% it is necessary to use all relevant options: energy savings, enhanced use of CHP, introduction of high-efficiency conversion technologies and abatement technologies, increased use of biomass and renewable energy technologies.

2.5. Total scenarios

Following these lines three main alternatives are constructed for the development of the Danish energy system until 2030. The alternatives are:

- **'Economic' alternative**(2)[2]: Comprises moderate investments in energy conservation, increased CHP-production, introduction of new conversion technologies such as combined-cycle and coal gasification and 1,500 MW windpower plants in 2030.

- **'Environment' alternative**(3): Comprises maximum achievable energy conservation in 2030, increased CHP-production, introduction of technologies such as combined-cycle and coal gasification, massive utilization of renewable energy (windturbines, wave energy, photovoltaics etc.)

- **'Supply' alternative**(4): Comprises moderate energy conservation, increased CHP-production, new conversion technologies such as fuel cells based on natural gas and coal, combined-cycle, coal gasification and 1,300 MW windpower plants in 2030.

As seen from Fig. 3 these three alternatives give a significant reduction in CO_2 emissions. Concerning the economic and the supply alternative, they reduce the annual system costs compared to the reference, at the same time. The annual cost of the reference amounts to 2.9% of GNP in the year 2030 (the same as in the year 1988), while the economic case reduces the annual costs to 2.7% of GNP in 2030. In the most far-reaching scenarios (the environmental alternative) the annual systems costs increase to 3.4% of GNP in 2030.

[2] Numbers in parentheses relate to the scenarios in Fig.3.

Further results of these three alternatives are shown in Fig. 4 and 5. Fig. 4 shows the development in gross energy consumption and Fig. 5 shows the total annual energy system costs in 2030 depending on the development of energy prices.

As seen from Fig. 5 changing the level of energy prices does not change the economic ranking of the scenarios, but having in mind the large uncertainties associated with the scenario analysis, the conclusion must be that the energy systems costs are virtually indistinguishable in the alternatives.

In Table VII below the consequences for SO_2, NO_x, and CO_2 emissions in the alternatives are shown. Table VII shows that in both the 'Economic', the 'Environment' and the 'Supply' alternative it is possible to reach remarkable reductions of SO_2, NO_x, and CO_2 emissions in 2030. In particular the 'Environment' alternative results in more than 60 per cent reduction of the CO_2 emissions from 1988 to 2030.

Table VII Emissions of SO_2, NO_x and CO_2 from the Danish energy system 1988 and 2030

	SO_2 emissions (1000 t)	NO_x emissions (1000 t)	CO_2 emissions (mill. t)
Reference alt.			
- 1988	232.9	159.2	47.4
- 2030	85.5	58.4	52.6
'Economic' alt.			
- 2030	54.2	44.0	22.7
'Environment' alt.			
- 2030	48.4	38.5	16.5
'Supply' alt.			
- 2030	80.5	50.9	29.2

Development of electricity consumption in the four scenarios is shown in Table VIII.

Table VIII Development of electricity consumption

	PJ
Reference alt.	
- 1988	101.0
- 2030	169.3
'Economic' alt.	
- 2030	123.1
'Environment' alt.	
- 2030	110.0
'Supply' alt.	
- 2030	149.0

Independent of scenario electricity consumption will increase, but in the environment alternative only by 0.2% p.a. In the economic alternative the increase will be 0.5% p.a.

2.6. The action plan

From these long-term scenarios an actual action plan is proposed until the year 2005. The main target for this plan is a reduction in the emissions of carbon dioxide of 20% in the year 2005 compared with 1988. To reach this target the following instruments are proposed:

- introduction of environmental taxes on CO_2 and SO_2
- introduction of environmental taxes on industry and services
- increase insulation standards for new buildings
- introductions of norms and standards for electrical appliances.
- encourage and develop the use of waste heat from power plants, especially from small scale CHP-plants
- increase the use of domestic resources (e.g. biomass) and the use of renewable energy technologies
- increase research and development in high-efficient CHP-technologies, as fuel cells and coal-gasification plants.

At the time being the Danish Government has an agreement with the utility companies of establishing 100 MW wind power and 450 MW decentralized CHP plants. This agreement is proposed expanded to the establishment of further 100 MW wind power before 1994.

It is estimated that the annual costs of the action plan will amount to 2.8% of GNP in the year 2005, compared with 3.1% of GNP for the reference case.

Fig. 6 shows the development in gross energy consumption for the action plan to the year 2005 in comparison with the reference case and the three main scenarios.

3. BRUNDTLAND PLANS IN OTHER NORDIC COUNTRIES

3.1. Norway

To study the relations between economic growth, energy consumption and environment a macroeconomic project called SIMEN: Studies of industry, environment and energy to the year 2000 (Statistisk Sentralbura, 1989), was carried out in 1988-89.

This project develops 4 main alternatives:

- **the reference case**: low economic growth, small changes in the industrial structure, a gradually increased foreign competitiveness.
- **the natural gas case**: increased use of domestic natural gas.
- **the environmental case**: reduced sulphur content in oil, increased use of abatement technologies, restrictions for the growth of the transport sector.
- **the tax case**: introduction of environmental taxes to reduce emissions of CO_2, primarily.

The results are shown in Table IX, below.

As seen from Table IX, emissions of SO_2 and NO_x can be reduced in more alternatives, while the emission of CO_2 can be stabilized only in the most far-reaching alternative.

Table IX Emissions of SO_2, NO_x, and CO_2 from the Norwegian energy system (1987 and 2030)

	SO_2 (1000 t)	NO_x (1000 t)	CO_2 (mill. t)
Emissions, 1987	88	245	36
The reference case, 2000	104	258	43
The natural gas case, 2000	102	255	48
The environmental case, 2000	79	240	43
The tax case, 2000	82	223	36

3.2. Sweden

The starting point of the Swedish energy and environmental planning work is a number of policy decisions in the Swedish parliament. The three most important of these are:

- the phasing out of nuclear power
- hydro power can not be further developed
- (at least) stabilization of the emissions of CO_2.

These were the main assumptions behind the Swedish energy and environmental scenarios.

Two main scenarios are developed:

- **a reference case**, and
- **an environmental case**, where a number of environmental taxes are introduced.

Both scenarios are considered for low and high economic growth, respectively. Results are given in Table X (Statens Energiverk and Statens Naturvardsverk, 1989).

Table X Emissions of SO_2, NO_x, and CO_2 from the Swedish energy system (1987 and 2015)

	SO_2 (1000 t)	NO_x (1000 t)	CO_2 (mill. t)
Emissions, 1987	120	72	41
Reference case, 2015			
- high economic growth	140	111	129
- low economic growth	95	74	81
Environmental case, 2015			
- high economic growth	90	78	54
- low economic growth	68	60	42

As seen from Table X, the assumption of stabilized CO_2 emissions (at least) can be obtained in the environmental case with low economic growth, only. Both low-growth scenarios result in a decrease in the use of electricity, by 10% in the low growth case and by 25% in the low growth environment case.

3.3. Finland

As a follow-up of the Brundtland report, the Finnish Ministry of Trade and Industry (energy department) has initiated a project on energy and environmental scenarios until the year 2025.

A number of scenarios have been calculated and two of the main scenarios are given below (Handels-og Industriministeriet, 1990):

- **the reference scenario**: a continuation of the existing trends, according to the lowest possible costs.
- **an efficiency scenario**: severe efficiency measures are introduced in industry, transport and households. Net energy consumption for heating are reduced by 20% until the year 2020.

The results are given in Table XI.

As seen from Table XI, it seems possible to stabilize gross energy consumption and emissions of CO_2 in the efficiency scenarios. Emissions of SO_2 and NO_x are expected to be reduced significantly.

Table XI Scenarios for gross energy consumption and related emissions from the Finnish energy system (1988 and 2025)

	Gross energy consumption (Mtoe)	SO_2 (1000 t)	NO_x (1000 t)	CO_2 (mill. t)
Status, 1988	29.6	240	260	50
Reference case, 2025	39.2	266	200	82
Efficiency case, 2025	30.2	200	130	53

4. OTHER WESTERN EUROPEAN COUNTRIES

4.1. General

The Brundtland report and the fear of the greenhouse effect have had a considerable impact upon the energy policies in several Western European countries. In general, the most comprehensive attempts are to:

- establish energy saving programs, including subsidy schemes, information campaigns, mandatory regulations and standards and increased R&D budget.
- increase the efficiency in the energy supply by introducing new high-efficient conversion technologies and expanding the use of combined heat and power.
- increase the use of renewables, e.g. by using grants and subsidies.
- introduce stringent emission standards and increase the use of abatement technologies.
- put more emphasis on low-emission fuels (e.g. natural gas).

Holland has prepared a comprehensive National Environmental Policy Plan, where the reduction of the greenhouse gas emissions is a central item. The Dutch government has thus decided to stabilize the CO_2 emissions on the 1989/90 level by 1995 and to achieve an effective reduction of 5% in the year 2000. These targets are mainly to be reached by an intensive use of subsidy schemes, regulations and standards.

Germany has recently launched a comprehensive energy plan, where a central aim is to reduce CO_2 emissions by 30% by the year 2005. This target will be achieved by the use of economic instruments (taxes and tariffs), mainly.

4.2. A common European Community agreement on stabilizing emissions of CO_2

By October 1990 the European Communities agreed upon a stabilization of CO_2 emissions at the 1990 level by the year 2000. Before 1992 the European Commission shall put forward proposals on limitations/reduction targets for the single member countries. This might have an impact on reducing the growth in electricity consumption, although it is hard to guess about that at the time being.

Table XII shows the policy plans for reducing CO_2 emissions for a number of EC countries. For comparison a number of other countries are shown as well.

5. CONCLUSION

During the past years electricity consumption in OECD-Europe has developed nearly linear - giving a stable absolute growth and slowly declining growth rates. Although the growth is unevenly distributed among countries, the pattern in aggregate seems reasonably stable with only a few exceptions due to energy crises.

The necessity of reduced emissions of e.g. carbon dioxide might change this growth pattern. In the case of the Danish Brundtland Plan it is shown that it is possible to reduce CO_2 emissions by 50% over a forty year period. In spite of these emission reductions electricity consumption will keep growing. In the environment alternative electricity consumption will grow very slowly, though.

Other Nordic countries have look into the CO_2 problem as well, although not as far into the future as Denmark. Concerning Sweden, the most drastic environment scenario can stabilize CO_2 emissions in the year 2015 at the 1987 level. But this necessitates a reduction in electricity consumption of 25% compared with today. A Norwegian study finds it possible to stabilize CO_2 emissions in the year 2000 at the level of today.

Holland and Germany have prepared comprehensive energy/environmental plans aiming at reducing the emissions of CO_2 considerably. By the agreement October 1990 the European Communities have committed themselves to stabilize the CO_2 emissions by the year 2000. Before 1992 the European Commission will put forward proposals on limitations/reduction targets for the single member countries.

Thus, several attempts are being made to reduce CO_2 emissions. But for most countries it will probably be difficult to reduce electricity consumption proportionally. Due to substitution towards electricity, even strong savings attempts will most probably only reduce growth rates of electricity consumption. In spite of this, the Danish case shows that it will be possible to reduce emissions of carbon dioxide considerably.

Table XII Single country policy plans for reduction/stabilization of CO_2 emissions (New Scientist, 1990)

Country	Contribution to world CO_2 emissions (%)	Policy plans
EC members		
- Belgium	0.5	Stabilize at 1988 levels by 2000
- G. Britain	2.8	Stabilize at 1990 levels by 2005
- Denmark	0.3	20% reduction by 2005
- France	1.9	Recommends 20% reduction by 2005, up to 50% by 2030
- Germany	3.2	30% reduction on 1987 levels by 2005
- Ireland	0.1	Stabilization at current level by 2000
- Italy	1.8	Stabilize at 1990 levels by 2000
- Holland	0.7	Stabilize by 1995, 5% reduction by 2000, followed by substantial cuts
Other European		
- Finland	0.3	Stabilize at 1990 levels by 2000 'at least'
- Norway	0.2	Stabilize at 1990 levels by 2000
- Sweden	0.2	Stabilize at 1988 levels by 2000
- Switzerland	0.2	20% cuts proposed
Australia	1.6	20% reduction by 2005
Canada	2.0	Stabilize at 1990 levels by 2000 'as a first step'
Japan	4.4	Stabilize at 1990 levels by 2000
New Zealand	0.1	20% cut by 2000
USA	22.0	Not in favour of emission controls
USSR	18.4	Not in favour of emission controls at present

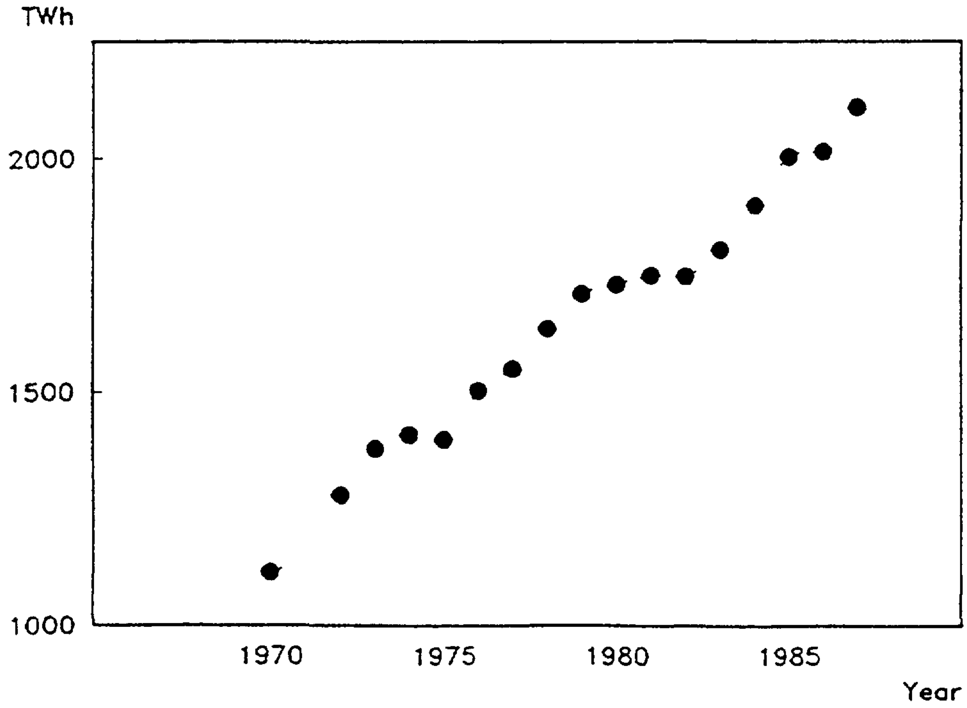

Fig. 1 Total electricity consumption for OECD Europe, TWh

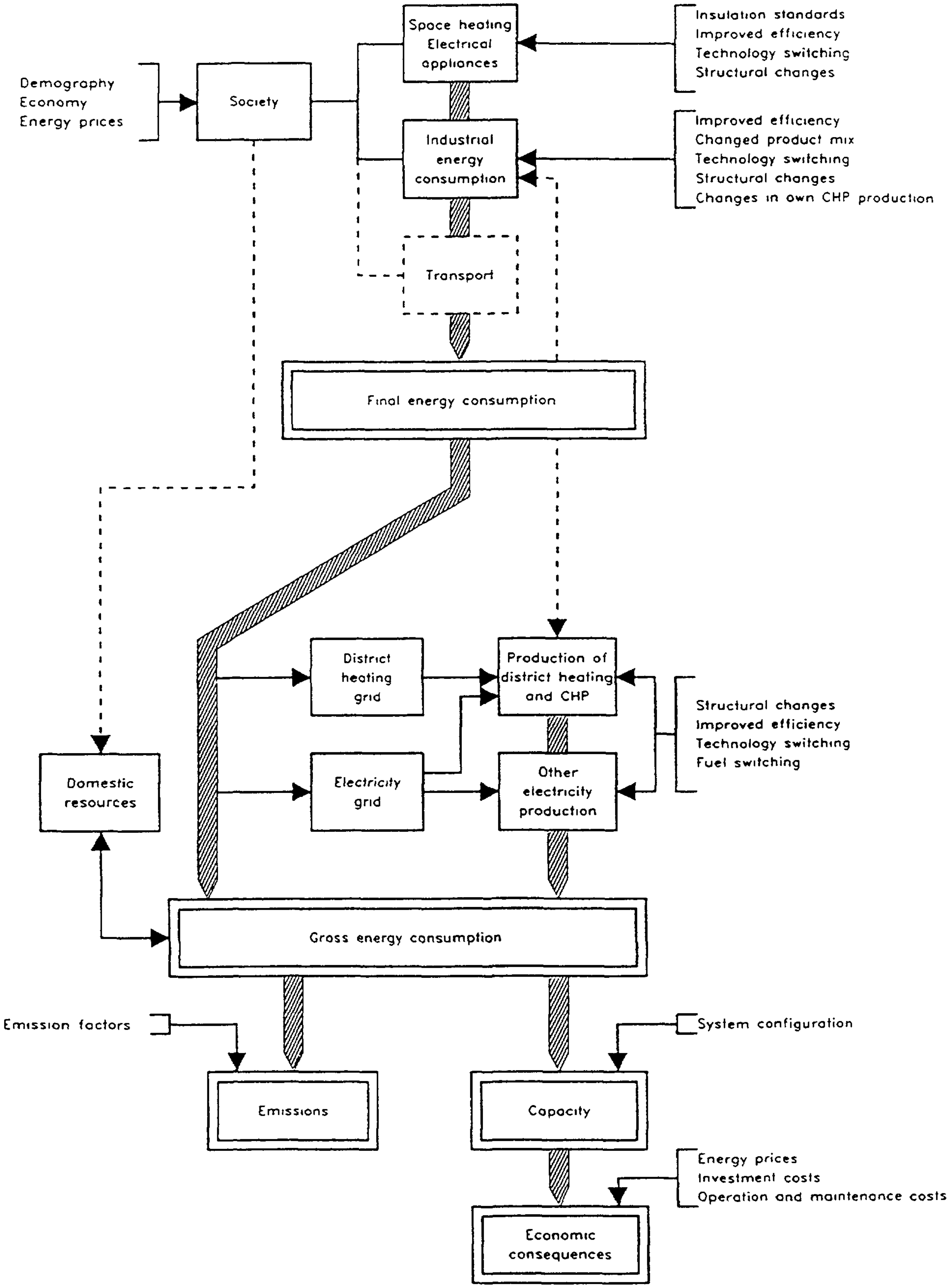

Fig. 2 The structure of the Brundtland scenario model (BRUS)

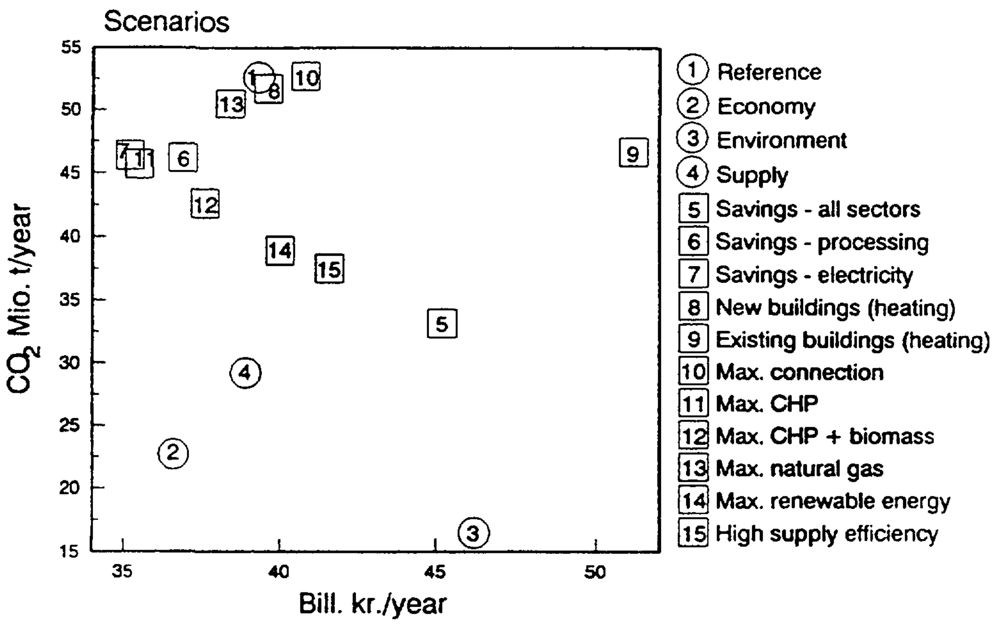

Fig. 3 Scenarios performed for the Danish energy system for the year 2030 (1 US$ = 6.0 DKK)

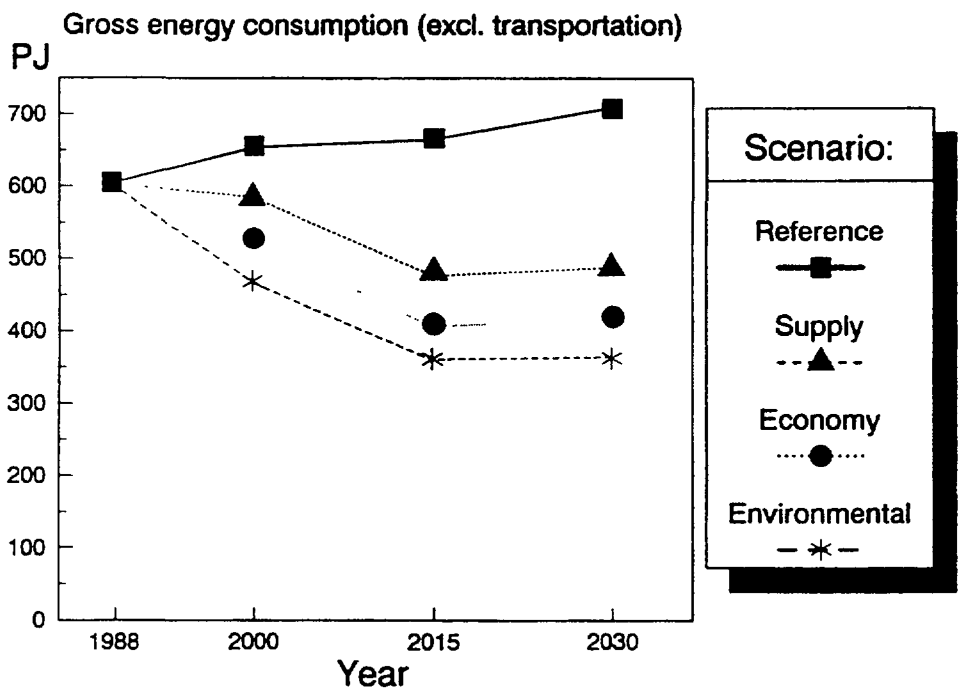

Fig. 4 Development in gross energy consumption, 1988-2030

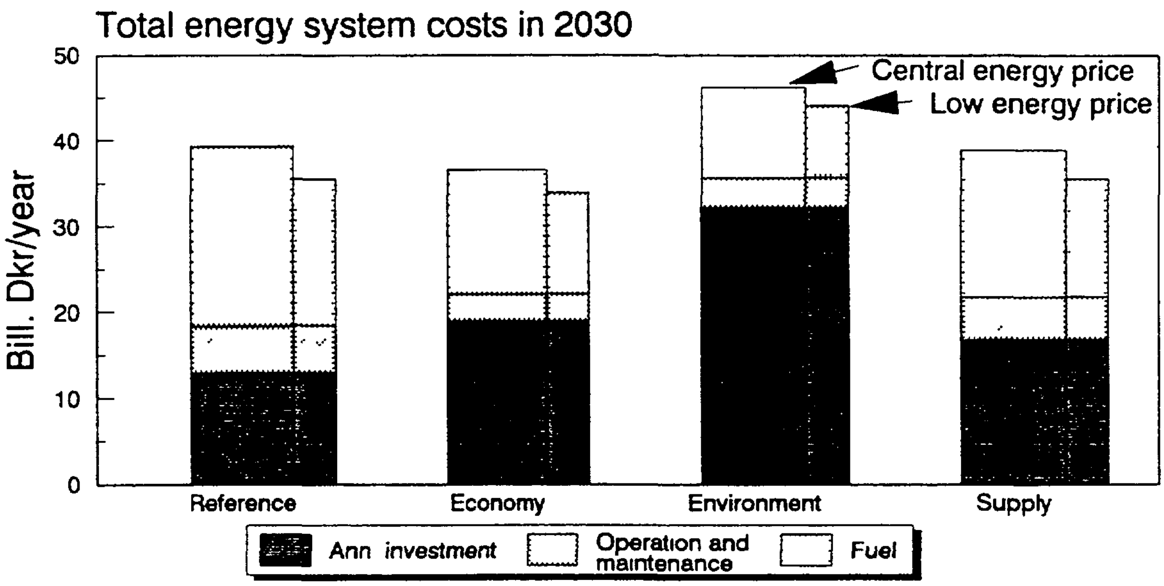

Fig. 5 Energy systems costs per year in 2030 connected to alternative scenarios (1 US$ = 6.0 DKK)

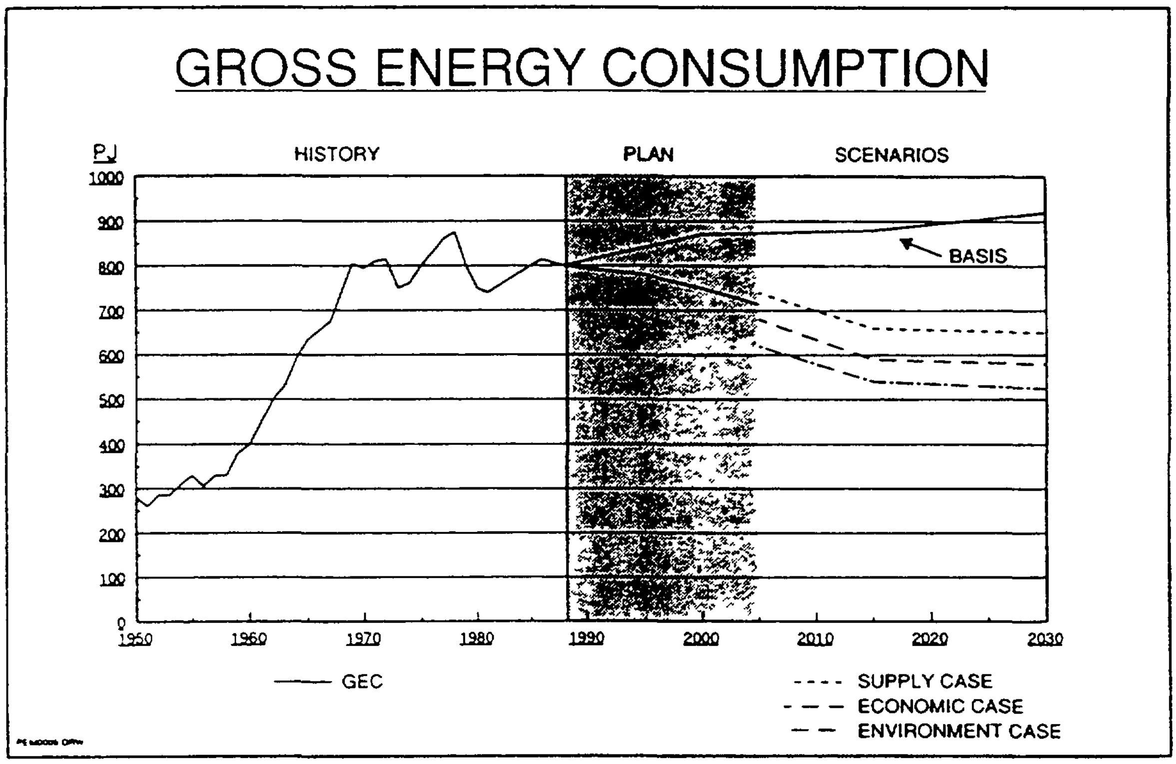

Fig. 6 Development of gross energy consumption, PJ

ELECTRICITY AND THE ENVIRONMENT: ISSUES FOR THE INDIAN POWER SECTOR

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ABSTRACT: The electricity sector in India, as in other developing countries is going through a crucial phase. The constraints imposed by the objective of limiting environmental emissions, is likely to create problems in meeting the rapid demand for electricity. This would result in shortfalls and the effect of this would have to be borne mostly by the population in the rural areas. The governments are in the process of identifying strategies that would enable them to reduce the gap between supply and demand. The strategies relate to increased energy efficiency in the power generation cycle as well as in the different end-uses. One of the major constraints is the availability of effective institutional framework to implement the energy efficiency programs. Increased energy efficiency would assist in achieving the twin objectives of reducing the gap between demand and supply as well as playing an important role in limiting environmental emissions. In addition to this is the need for an efficient pricing structure for electricity which would send the correct signal to the consumer regarding the real cost of electricity. One of the important points that emerges is the need for greater cooperation, particularly with the developed countries for transfer of energy efficient technologies. The major constraints relate to absence of the necessary institutional framework and efficient pricing systems. It is important that these areas receive immediate attention in order that the benefits arising out of increased efficiency could yield the necessary results.

1. BACKGROUND

The power sector in India is gearing up to meet the rapid growth in the demand for electricity. Simultaneously, the power sector is also seriously concerned about the environmental impact of its policies and is in the process of identifying the options available to achieve the twin goals of meeting the demand for power, while minimizing the environmental impact. The demand for electricity is expected to only increase as incomes go up, more of the population moves into urban areas, and the standard of living increases. As against this, are the financial constraints that are likely to increase the gap between demand and supply. Adding the cost of limiting emissions, will only result in widening this gap.

It must be mentioned that this is a feature that is common to almost all the developing and the less developing countries. However, in the context of the Montreal Protocol and the discussions taking place at the Inter Governmental Panel on Climatic Change regarding strategies to limit emissions, it is important that the power sector makes it contribution to the entire exercise.

This paper examines some of the options that are available to reduce the gap between the ever growing demand and the limited supply, as well as identify some of the major constraints that would come in the way of implementing these options. The constraints are by no means impossible to over come as will be seen in the later portion of this paper. We begin with a brief overview of the developments in the power sector in India.

2. POWER DEMAND AND AVAILABILITY

The ease and convenience with which electricity can be used for a variety of applications has resulted in a sharp increase in the demand for electricity in India. The power sector has played an important role in India's economic development. Industrial activity got a major boost, small industries picked up, the agricultural sector benefitted by the use of pump sets, particularly in the drought periods. The increased availability of power to the domestic consumers saw a boom in the use of electrical appliances, particular, electric lighting, water heating, space cooling, television, refrigerator etc. The coming decade is likely to see a sharp upswing in the use of washing machines, air-conditioners, room heaters, as well as for cooking. The rapid electrification of rural areas is also adding to the already increasing demand for electricity.

2.1. Organization of the power sector in India

The Electricity Supply Act of 1948, provided for the creation of electricity boards in each state (SEB), which were charged with the responsibility of generating, transmitting and distributing the power in a state. This act also envisaged the creation of a central body, the Central Electricity Authority (CEA), with the objective of evolving a national power policy as well as coordinating the activities of the power sector in the country. The Act was amended in 1976, to permit entry of central sector organizations in the power sector. The National Thermal Power Corporation and the National Hydroelectric Power Corporation were created to take advantage of economies of scale and to cater to the needs of power in several states. These were basically generating companies, and power was sold in bulk to the states. Besides these, there are a few other generating companies such as the Neyveli Lignite Corporation, the

Damodar Valley Corporation etc. which also generate power for sale to the SEBs. Nuclear power is the responsibility of the Nuclear Power Corporation. There are three private utilities that generate, and sell power to consumers in their licensed areas.

2.2. Installed capacity and generation

Installed capacity has increased from 1,712 MW in 1950 to 63.38 GW as at the end of March 1990. The growth in capacity and generation is given in Figures 1 and 2. It is seen that the installed capacity has doubled almost every ten years. Also, thermal capacity accounts for 68% of the total installed capacity and accounts for 73% of the total generation. Gross energy generation has increased from 5.1 TWh in 1950 to 251 TWh, in 1989-90 registering an average growth rate of 10% during last four decades. Nuclear power still has a very small share in the installed capacity (1,465 MW) and accounts for only 2% of the total energy generated.

2.3. Pattern of consumption

Electricity consumption has grown at 8% compounded during the period 1970-71 to 1986-87. As against this, consumption of oil and coal grew at 5 and 5.5% respectively. There has also been a structural change in the consumption pattern over the last three decades. The changes are:

- the share of industries has declined from 75% in 1960-61 to 62% in 1970-71, and further down to 44% in 1988-89.

- The share of the domestic and commercial sector increased from 14% in 1960-61 to 26% in 1988-89.

The state governments have launched massive rural electrification programs in order to provide supply to rural consumers. Village electrification programs have progressed rapidly, with the number of villages electrified, increasing from 3,000 in 1950-51 to 464,480 as at the end of January 1990. Several states have already achieved 100% electrification, while several others would have achieved this by 1994-95. The per capita consumption, which was around 15 units in 1947, has grown to 234 units in 1989-90.

2.4. Reliability of power supply

Though the progress of the power sector during past four decades has been substantial in absolute terms, the power industry has been unable to fulfill the primary obligation of providing quality power supply in required quantity. The major reason for this being the demand for electricity has been increasing rapidly outstripping its availability. As a consequence restrictions are imposed from time to time, on both peak demand and energy. The consumers who are affected are the industries (both LT & HT), large commercial consumers and the consumers in the rural areas, agricultural as well as domestic. The industries have installed captive diesel sets to overcome the shortage problem, partly or completely. The introduction of small diesel units in the kilowatt range has resulted in the domestic/commercial sectors also resorting to them, for use during unnotified power cuts. This not only causes undue inconvenience as in the case of domestic and agricultural consumers, but also results in shortfalls in production targets in several industrial sectors.

2.5. Environmental concerns

The issues relating to the environment have assumed importance in the last decade, particularly with the threat of global warming. The Ministry of Environment and Forests, in the Government of India, is charged with the responsibility of identifying strategies to contain environmental damage. To this extent, all power stations (as do other sectors of the economy) have to submit environmental impact statements which give information on the steps taken to maintain emissions levels in the case of thermal and nuclear stations, and regarding protection of the environment and resettlement and rehabilitation of the population in the catchment areas for hydro power stations. Even the transmission programs have to take clearance regarding right of way through forests etc. In spite of the steps taken by the ministry, the utilities have not really realized the seriousness of the problem. The chapters containing steps for controlling emissions are quite sketchy and power projects get delayed for reasons of not providing enough data in this important area. Large hydro projects have of late attracted the attention of environmental groups and these have rightly or wrongly taken the issue of environmental damage by large hydro power projects beyond proportions. In the entire process, the only thing that happens is the project gets delayed by a couple of years or more and there is a cost overrun as well.

The Central Air Pollution Board is responsible for setting air and water quality standards and is also responsible for enforcing them. Under constraints that they operate, it must be said that they have been able to enforce these standards to a limited extent. There are offices of this board at the state level and these assist in the various activities regarding maintenance of standards.

Thermal capacity presently accounts for about 68% of the total capacity installed in the utilities and accounts for 73% of the energy generated in the country. The power sector presently accounts for about 50% of all the emissions responsible for global warming in India. This includes CO_2, CO, CH_4, and NO_x emissions. Among the various emissions released by combustion, carbon dioxide emissions are considered to be the most critical variable. The power sector accounts for over 96% of the total carbon dioxide emissions in the economy. There are standards for emissions of CO_2, SO_x and NO_x. Electrostatic precipitators have been installed in almost all the newer power stations and although there have been some problems regarding their operations, their performance by and large has been satisfactory. The Bureau of Indian Standards in close cooperation with the concerned ministries is in the process of bringing out the necessary standards.

3. FUTURE SCENARIO

3.1. Demand and supply

According to the 13th Annual Power Survey Committee, it is estimated that on all-India basis, the peak demand by the end of 1994-95, which is the terminal year of the Eighth Five-year Plan, will be of the order of about 73 GW and energy requirement will be of the order of 385 TWh. Capacity addition to the tune of 38 GW is envisaged during the Eighth Five-year Plan. However, even after full implementation it is expected that there would be a shortage of about 12.7 GW in the peak demand and 7,400 GWh in energy requirement on all India basis (see Table I for details).

The 13th Annul Power Survey Committee also estimated that the peak demand and energy requirement would be of the order of 174 GW and 919 TWh respectively, by the year

2004-05. This is indicative of an installed capacity of 287 GW as against an installed capacity targeted of 104 GW for the year 1994-95. Under the present situation of shortages and addition to capacity, it is difficult to see a scenario where shortages would not be present.

Table I. Power Projections for 1994-95 (surplus(+), deficit(-))

Region	Maximum demand (MW)	Energy requirement (GWh)
Northern	- 4338	+ 6216
Western	- 3528	- 3516
Southern	- 3868	- 17931
Eastern	- 1181	+ 2997
Norteastern	+ 273	+ 4924
A & N Islands	- 37	- 52
Total	- 12679	- 7362

Source: Seventh Plan Review and Eighth Plan Issues and options, Options, Bahadur Chand, Chairman, CEA, January 1989

Thermal capacity would continue to be the mainstay for the Indian power sector considering the fact there are large reserves of coal in the country. It is expected that an additional 50 GW of coal based capacity would be added during the next ten years. The increased availability of natural gas has given a new direction towards gas based power stations, operating in the combined cycle mode, as base load power stations. Also, the short gestation periods for gas stations, makes it more attractive for the power sector to reduce the gap between demand and supply. The fact that gas based power generation is environmentally attractive adds to the emphasis for these stations. It is expected that gas based power station would yield about 5-8 GW in the next 10 years.

It must be pointed out that the carbon intensity (defined as kg of carbon per additional GWh energy generated by the electricity sector) is low for India (122.36) as compared to China (176.79), Mexico (154.7) or Korea (175.31)[1].

3.2. Power sector finances

The cumulative losses of the SEBs as on 31st March 1990, is estimated at US$ 1.8 billion (one US$ = Rs. 18.00)[2]. The major reason for this being the unremunerative tariff policies of the boards. Several boards do not even recover the average cost of supply and hence the question of earning a surplus does not arise. The dues to the state governments by way of interest and loans are often adjusted against subsidies receivable and on the boards allocation for capital expenditure. As a result of this, there is a mix up of the revenue sources and capital

1 W. Templitz-Sembitzky, 'The LDC Power Sector A Brief Overview and Global Outlook', prepared for the Senior Expert Symposium on 'Electricity and the Environment', to be held at Helsinki, May 13-17, 1991

2 Annual Report on the Working of the State Electricity Boards and Electricity Departments, Planning Commission, May 1990

budgets. The question of a rational tariff structure has been discussed in several forums, but a workable consensus is yet to emerge.

Plan allocation for the power sector, has been between 17-18 per cent of the total plan outlay. In absolute terms, the outlay for the power sector has been doubling every five years. In spite of this, funds availability for the Eighth Plan is expected to be a major constraint. To meet the target of 38 GW capacity addition during the Eighth Plan, funds to the amount of US$ 67 billion will be required. This means the share of outlay for power sector in total plan outlay will have to increase from 20% to over 30% in the Eighth Plan. Even though the allocations have not been finalized, indications are that it may be around US$ 36-40 billion.

The consequence of this would be that money would continue to be put into generation activity, and the transmission and distribution would continue to lag behind due to paucity of funds. This would lead to an insufficient T&D network and this means increased T&D losses. Losses which are currently around 22-23% at the all India level, is expected to reduce to a reasonable level of 18% by the turn of the century. But with this trend of finances available for T&D schemes, it would be difficult to expect that this reduction would be achieved.

Considering the fact that demand shortages would continue into the Eighth and Ninth Plans, it is imperative that measures are identified that would enable a marginal, if not completely reducing the shortages. As mentioned earlier, the environmental considerations are likely to push us towards increased efficiency. In the following sections, the various options are discussed and this is followed by some of the constraints that are likely to reduce the effectiveness of the options for meeting the twin objectives of meeting the demand for electricity, while ensuring that the environmental considerations are also duly accounted for.

4. DIRECTIONS FOR THE FUTURE

The Government of India has constituted a Working Group and several subgroups to identify the various options that would go towards reducing the gap between demand and supply. At the same time, there are other groups engaged in the task of working out strategies to contain the damage to the environment from the power sector. The options fall into two broad classes:

(a) Technology options, which would lead to increased efficiency in the entire power generation and consumption cycle; and

(b) fiscal and pricing options.

The first option would also include substitution possibilities such as renewable options which are environmentally more benign as compared to conventional power generation options. It must be mentioned that the two options are linked very closely as it is ultimately costs and prices that would decide the direction which would be taken; e.g. some of the renewable options are likely to compare favorably with thermal power, if the government were to add elements of subsidy to renewables or tax the conventional power sources. Hence it is important to carry out an economic evaluation at the first stage and then adjust these costs and prices with subsidies and/or taxes in order to indicate the direction towards which the economy would have to move. Some of the options are discussed below.

4.1. Increasing efficiency in power generation

The average gross conversion efficiency for thermal generation is 28%, and the average net efficiency is about 25%[3]. More than 70% of the installed capacity in thermal stations operates at efficiencies below 30%, and 25% of capacity operates at efficiencies even below 25%. Currently, worldwide, operating efficiencies are close to design efficiencies and are about 35%. Enhancing power station performance to increase operating efficiency would increase their power output (at the same coal input rate) by nearly 15%: implying that CO_2 emissions per kWh generated would decrease by nearly 12%.

Auxiliaries in thermal power stations consume about 10-12% of the installed capacity. It is possible to reduce the auxiliary consumption adoption of energy efficient accessories, in order that this is reduced to about 8%. Decrease in in-plant consumption would, therefore, also result in a reduction in specific CO_2 emission (kg carbon emitted per kWh delivered at station busbar).

Coal supplied to TPS is largely from open-cast mines and has a lot of non-coal material (principally shale and rock) mixed with it. Hence, washing the coal before it is supplied to power stations would greatly reduce the non-coal matter that travels with it. Boiler efficiency with washed coal rises to about 89.5%[4], and in-house electricity consumption reduces from 10 to 8% of gross generation[5].

4.2. Increased use of natural gas for power generation

Substitution of coal by gas to the extent possible would also reduce CO_2 emissions. Current plans for gas based TPS call for an addition of 7,745 MW during 1990-95. Additions during 1995-2000 would probably be about 10 GW. Apart from these plans, all the gas presently flared off the West coast could be utilized for power generation in West India which would release an equivalent amount of coal.

Currently, over 2.5 billion cu.m of natural gas are flared in the Bombay High basin annually[6]. This gas could generate about 12 TWh of electricity which implies an installed capacity of about 2.2 GW of gas based combined cycle TPS, or an equivalent 2.5 GW coal based TPS using 8.5 Mt of coal per year. This is a strategy that needs a closer look.

4.3. Transmission and distribution

Transmission and distribution (T&D) losses in the Indian power system are estimated at 22%[6]. However, owing to the practice followed by some State Electricity Boards (SEBs),

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[3] Public Electricity Supply, All India Statistics, General Review 1986-1987, Central Electricity Authority, Government of India, New Delhi, 1990.

[4] Report on Trial of Beneficiation of Non-Coking Coal from Nandan Washery at Satpura Thermal Power Station, National Productivity Council, Calcutta.

[5] Report on the Committee to Evaluate Beneficiation of Non-Coking Coal for Thermal Power Stations, Planning Commission, Government of India, New Delhi, 1988.

[6] TERI Energy Data Directory and Yearbook, 1989, Tata Energy Research Institute, 1990.

of diverting a certain portion of non-technical/commercial losses towards unmetered power supply to agricultural consumers, the actual T&D losses may be somewhat higher.

The Committee on Power[7] recommended a somewhat realistic target of reducing T&D losses to a level of about 15% by the year 2000. Of course, little has been done in this direction so far. In fact, percentage T&D losses increased until the mid-1980s, from 17.5% in 1970-71 to 21.5% in 1987-88, and have remained fairly stable since then.

Analysis shows that losses at the transmission level are quite under control at about 4.5-5.5% and it is the losses at 11 kV and lower voltage levels that are to be checked. These also include non-technical losses, arising from under-recording in meters (most mechanical meters tend to slow down with age), meter tampering, defective meters, and pilferage etc. Losses arising from the latter three factors may be reduced with more care in testing and replacement of meters in time, and strict enforcement of laws to ensure that meters do not get tampered and that electricity theft does not take place. Also, a coordinated program of periodic meter-testing and recalibration needs to be introduced. It is understood that some utilities have established meter-testing laboratories, but their achievements and performance levels need to be upgraded.

It is very clear that the T&D system needs to be strengthened. A mere 1% reduction in T&D losses could generate resources enough to meet 2 to 3% of annual plan outlays of Electricity Boards. A system of energy auditing must be propagated, so that it is possible to access the technical and commercial losses separately and then to take steps to minimize them. To reduce commercial losses, bills must be issued in time, collected in time and energy theft must be regarded as a cognizable offense and serious steps must be taken against it. Technical losses can be reduced by system improvement conversion of LT lines to HT lines, improvement of power factor, use of superconductors to carry very large currents without loss.

4.4. Energy efficiency in end-use

The Government of India had set up an Inter-ministerial Working Group[8] to identify areas where energy efficiency could be undertaken, to estimate the likely investments and the nature of savings that could be realized. The working group estimated that up to 25% savings could be realized in commercial energy consumption in the different end use sectors (including coal, and petroleum products). The working group had estimated that an investment of the order of US$ 3 billion (at 1982 prices) would be required to get the benefits by way of reduced specific energy consumption.

In the short term, just by the adoption of good housekeeping practices is reported to yield a reduction in consumption of about 10-15%. In the medium term, use of waste heat recovery units, replacement of over-aged equipment with energy efficient equipment, introduction of control systems is expected to reduce consumption by about an additional 10%. In the long term, measures such as cogeneration, adoption of energy efficient technologies, computerization of process control operation, etc. would yield a reduction of about 20% in specific energy consumption.

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7 Report of the Committee on Power, Planning Commission, Government of India, New Delhi, 1980

8 Report of the Inter-ministerial Working Group on Energy Conservation, Government of India, New Delhi, 1983

In the industrial sector, the large consumers, such as petrochemicals, aluminum, steel, cement are carrying out exercises to reduce energy consumption and it is the medium and small industries where efforts need to me made in order to bring down the consumption in these industries. Lack of awareness, limited finance, and an absence of total commitment from the top management are some of the factors that are coming in the way of achieving energy efficiency targets. Added to this, is the absence of any incentives for achieving energy efficiency targets, high interest rates, high duty on imported equipment also add to the problem.

The agriculture sector is an area where enormous potential exists, but this is also the area which is likely to have the maximum problems. It is estimated that 70-80% of the 8.5 million pump-sets installed in the country are inefficient and retrofitting is likely to yield a reduction in energy consumption by about 25-30%. The efforts in this area have been quite fragmented and there is a need to launch an all-India coordinated project in this area. The extremely low flat rate tariffs for farmers only adds to the complications. There is virtually no incentive for the consumer to go in for a more expensive, although an energy efficient pump-set. It is of utmost importance that a workable program is launched in this area, since, it is expected that another 3 million pump-sets would be added in the next ten years. The increase in the usage of electrical appliances in the domestic and commercial sectors makes it one of the important areas for increasing energy efficiency. Again, the large number of consumers (running into millions), limits the success of any program launched in these areas. Energy efficient lighting (tubelights, compact lamps etc.) can alone reduce the energy consumption by more than 25-50%. Increasing efficiency of water heaters, refrigerators, air-conditioners, can result in additional 20%. These measures would indirectly have an impact by way of maintaining emissions at existing levels, considering the growth in consumption.

Estimates show that incremental carbon dioxide emissions could be reduced by about 10-15% as compared with the option of business as usual scenario.

4.5. Pricing measures for demand management

As mentioned earlier, prices for electricity are fixed by the utilities, with a view to recover the costs of their operations. Measures such as tariffs based on connected load, irrespective of usage, have led to a situation, whereby the utilities have had to incur substantial losses, have not helped. The issue of time-of-day tariffs for peak load management have also not been given due consideration. Two utilities have experimented with some form of peak load pricing with mixed results. One of the major constraints in implementing such a pricing scheme is the availability of meters of good quality. It is possible that application of peak and off-peak tariffs whereby a higher tariff for peak hours and concessional rates for off peak hours may encourage the consumers to shift their consumption from peak hours to off peak hours. As in other countries, a beginning should be made by identifying HT industrial consumers who are likely to respond to such a scheme.

Sensitivity studies have indicated that if the peak load could be reduced by 10%, while maintaining the energy requirements at projected level, the capacity requirement by the end of the Ninth Plan would be reduced by about 9 GW which could reduce the overall investment by about US$ 9 billion.

Prices have never been considered from the point of view of energy conservation. Block rates for domestic and commercial consumers could be used to charge the better off consumers who consumer more than 200 kWh per month, at or above marginal costs, and the poorer consumers to be subsidized. While the commercial consumers are being charged a stiff rate, even the domestic consumer who consumes more than 300-400 kWh per month have low tariffs. Also utilities have never considered having a rebate or concession for any program connected with energy conservation.

4.6. SEBs direct participation in energy conservation schemes

'Energy conserved in energy saved', is an oft repeated phrase. The government, the financial institutions have launched several financing schemes, where soft loans are given for energy conservation schemes. But the electricity boards who would benefit the most are yet to take a direct interest in conservation. Utilities in developed countries (USA, Europe etc.) see energy conservation schemes as an economic option to capacity additions. Utilities in these countries have carried out investments in energy efficient lighting systems, in housing heating/cooling retrofit schemes as well as in industrial energy conservation schemes. Their investments have been more than paid back, by way of reductions in future stream of investments.

The SEBs could request the large industrial and commercial consumers to carry out energy audits and submit proposals on energy conservation which could be jointly funded by the utility and the consumer. Since both stand to benefit, a scheme to share the savings could be worked out which ensures payback of the investments made.

In the case of agricultural sector, the low tariff encourages wasteful practices like installation of pump-sets of higher power than needed, continued use of poor quality, low price parts which increase energy consumption. It has been found that the capacitors for power factor correction, often do not function at all.

What has been lacking in our efforts to promote energy conservation is absence of measures that penalize wastage of electricity. Attempts should be made to lay down energy norms for various industries as well as agricultural sector and a system of penalties should be introduced. On the other hand units who have been successful in conserving energy should be publicly honored and rewarded. Fiscal concessions should be given to promote energy efficiency schemes and liberal finances for adoption of energy conservation devices should be introduced.

In addition to all this, there is a need to create increased awareness on the need to conserve energy. Strong public awareness drives like training programs, lectures, seminars etc. must be organized not only for industries, but for commercial and domestic consumers as well.

4.7. The renewable option

Renewable sources of energy could be a strong option, particularly with limitations placed on the level of emissions from the power sector. Renewables would be specially attractive substitutes for conventional power, in places which are far away from the existing grid supply and where the utility has plans for extending their grid. Grid extension is an expensive proposition and this also entails increased losses in the system due to the long lines that would have to be laid and added to this is the low load factors of the loads in the rural areas. Even at the present costs there are many applications in which some renewable energy technologies are cost effective in addition to being environmentally benign.

In the power sector, for example, windfarm power generation competes favorably with the cost of thermal power. In the past five years, the Department of Non-conventional Energy

Sources (DNES) has commissioned a total of 10.1 MW of wind turbines which have fed over 22 million kWh of electricity to the central grid at costs averaging in the range of 5-8 cents kWh. The estimated costs in the future are expected to be as low as 4.5 cents kWh and DNES proposes to add as much as 5 GW of wind-power capacity by 2000 A.D. A study by the Tata Energy Research Institute[9] estimates the potential of windfarms in India at about 16 GW while the estimate of DNES is around 20 GW. In reality the ultimate potential for harnessing wind for power generation is much higher and would depend on the development of low cost energy storage systems in order to increase the penetration.

The potential for solar energy applications is also very large, particularly where energy requirements are in the medium temperature (100-150 °C) range. Increased adoption of solar energy can have a significant effect on the reduction of fossil fuel consumption.

The Department of Non-conventional Energy Sources have drawn up plans to add over 10 GW of equivalent capacity from renewables. Even though the targets are quite ambitious, even if we were to achieve a target of 5 GW from renewables, the relief to the electricity sector would be enormous. This would also assist by way of substantial reduction in the carbon dioxide emissions and thus, the benefit would be two-fold.

If one goes by the financial constraints and the current trends in financial allocation, it seems unlikely that the requisite funding for the proposals will be forthcoming. As pointed out, part of this has to do with the supply oriented approach to energy planning in India which places emphasis on addition to energy production capacity.

It is in this context that 'end-use planning', where the service provided by energy rather than energy available is considered. The end use approach, in conjunction with the actual cost of delivered energy, also leads to a realistic assessment of the cost effectiveness of different source-technology-end use combinations from the viewpoint of the society. When this procedure is followed, it is possible that even the 'expensive' photovoltaic technology is cheaper than providing the same energy service by extending the grid at many places in India. The cost effectiveness of other commercially available renewable energy technologies for irrigation such as windmills, gasifier and biogas based dual fuel engines, biomass based Sterling engines are better and less ambiguous. The same is true for many other energy end uses such as rural lighting, motive power for many small-scale industrial requirements, medium and low temperature thermal energy requirements in both, the domestic and the industrial sector, energy for refrigeration in health care, telecommunication in remote areas, and so on. The potential of renewable energy sources and related technologies, therefore, is immense.

Availability of technology for meeting these diverse end uses is not the main problem. The major problem lies with the low priority attached to the renewable energy sector and the lack of funds earmarked for the utilization of these energy resources. For example, in the Seventh Plan period while the power sector received over US$ 19 billion, the total allocation to the renewable energy sector was a limited US$ 300 million.

It would, however, be misleading to give the impression that all the renewable energy technologies have achieved the level of maturity or sophistication that is associated with the

[9] J. Hossain, An Assessment of Potential for Installation of Windfarms in India, Paper presented at the PACER Conference on Role of Innovative Technologies and Approaches for India's Power Sector, Organized by TERI and PFC, Delhi, April 1990

conventional routes to energy conversion. Here also, part of the reason can be attributed to the lack of funding to the renewable energy technologies. Therefore, the question of resource mobilization for development of non-conventional forms of energy is critical to the whole program in this area.

5. CONSTRAINTS TO FUTURE OPTIONS

The various options mentioned above are not all that smooth and easy to implement. The rapidly growing demand for electricity coupled with finance constraints are likely to result in a curtailment of services and shortages are likely to continue. Some of the constraints are discussed below.

5.1. Institutional framework

The state electricity boards are currently responsible for generation, transmission and distribution of electricity in the country. As far as energy conservation is concerned, the Energy management Center, an autonomous organization under the Department of Power is responsible for coordinating the activities in this area. The states have a nodal agency charged with the development of renewable energy at the state level and the funds for which are mainly from the DNES, at the center. They have not been really able to mobilize the activities necessary for propagation of renewable energy sources. Also, there is no agency at the state or district level to coordinate energy efficiency activities. There is a crucial need to strengthen the institutional framework enormously if results are to be achieved in this area. Rectification of agricultural pump-sets, which is reported to save up to 30% of the energy consumed, has been constrained by the absence of institutions to carry out rectifications and more important to monitor the savings.

5.2. Financial constraints

As already mentioned earlier, the economy is facing a resource crunch and this is likely to affect the power sector also. At the same time, the planners have seen the need to allocate substantial sums for energy efficiency activities. It is possible that lack of implementable activities may be more of a constraint rather than finances, as far as energy efficiency is concerned. This is an important area where international cooperation can enable the bringing of energy efficient technologies into the country in order that we can benefit from the developments in other parts of the world.

5.3. Promotion and awareness

This is an extremely important component of any program that can either make it succeed or fail. The awareness for energy efficiency is poor. The consumer may want to conserve energy but is not aware of what can be done to reduce energy consumption. This is true of domestic, commercial and industrial consumers. It is only recently that the Government of India launched a massive promotional campaign for increased awareness in energy conservation. There are also large scale plans for having several activities at the district, block level for providing information to the consumers on energy conservation. There is a need to set up demonstration centers where the consumers can see the benefits arising out of energy efficiency.

6. CONCLUSIONS

Increase in population, increasing urbanization, increase in standard of living, increase in the use of comfort related appliances, all these are factors that would contribute to the continued increase in the demand for electrical energy. In view of this, it is necessary not only to identify strategies, but convert them to implementable activities that would assist in meeting the challenging task of providing adequate quantity of quality power at the lowest possible cost to the consumers, while at the same time managing to control the damage to the environment.

ENERGY AND ELECTRICITY DEMAND AND THE FUTURE OF THE ELECTRIC POWER SECTOR IN THE USSR

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ABSTRACT: This paper reviews the past evolution of the USSR energy production and consumption, its present peculiarities, and discusses short and long-term possible energy futures taking into account the economic transition and the environmental concerns. Energy balances by 2000 and several scenarios of development by 2030 are described. Main potentials are identified both on demand and supply side to aim at an optimized energy system: structural changes in the economy, energy conservation, efficiency improvements, availability of large gas and coal reserves. However, while a sustainable path is achievable, the Soviet Union faces major uncertainties about economic growth and institutional changes since transition towards market policies has no historical analogy.

1. HISTORY AND PRESENT SITUATION

With 17% of the Earth's dry land and 5.4% of the world population the USSR possesses 20% of the proved resources of gas, 15% of coal and 6% of oil. In the early 1980s the Soviet Union became the largest producer of primary energy in the world with 21% of the total.

By the end of 1980s the USSR economic development slowed down to a critical point caused by previous negative processes, institutional changes and problems of transition towards market economy. In previous years the USSR produced enough energy to meet domestic demand and even to export. Now the energy sector is facing considerable difficulties dramatically enhanced by the Chernobyl accident, poor ecological situations in several regions, social and political shocks. As a result electricity and heat supply shortages occurred lately in several regions and oil export decreased. The decline of economic growth is shown in Fig. 1 [1]. Absolute numbers[1] in billion roubles are shown in Table I.

Table I GDP and national income in the USSR (1980-1989)

Year	GDP (billion roubles)	National Income (billion roubles)
1980	619	462.2
1985	777	578.5
1986	799	587.4
1987	825	599.6
1988	875	630.8
1989	924	656.8

In 1990 the situation became even worth; absolute figures of GDP in the first half of the year decreased by 1% compared with the same period of 1989 and national income by 2% [2].

Primary energy growth was more stable with 3.5% to 4.5% per year for production and 3.5% for consumption.

Tables II and III show energy balances of the previous 20 years [3, 4, 7].

The increase of primary energy production in recent years was mostly due to gas. This industry continues progressing while in coal and oil sectors the development is very slow. In the first half of 1990 oil and coal output even decreased compared to the production of the first half of 1989 [2].

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[1] In annual current prices. Values of the USSR GDP in US$ are being discussed now. Estimations vary by a factor of four, according to various sources. Methodological difficulties include possible production overestimations, coherence with criteria adopted for national accounting in market economy, uncertainty on the exchange rate of roubles versus dollar, inflation rate, etc.

70% of the primary energy is consumed in industry, agriculture and construction, but the trend is to a slow reduction of the share of those sectors upon time.

Table II USSR energy balances (Mtoe)

	1970	1985	1988	1990 (expected)
Primary energy production	895	1534	1697	1845
of which:				
- solid fuels	344	336	352	347
- oil incl. condensate	356	603	619	630
- gas	164	510	623	679
- hydro	31	49	52.4	56
- nuclear	0.7	42	45.6	60(40)[1]
Export	117	242	313	—[2]
of which:				
- coal	19	21		—
- oil	95	165		—
- gas	3	56		—
Primary energy consumption	788	1297	1390	1502
of which:				
- power sector	132	214		259
Final energy consumption	594	932		945
of which:				
- residential and commercial	118	202		217
- industry and agriculture	352	526		595
- transport	81	113		133

Notes: [1] In brackets - most likely
[2] Uncertain (export shortages took place in 1990)

About 75% of the electricity is generated by thermal power plants, 15% by hydro power plants and 10% by nuclear reactors. More than a half of the electricity generated is consumed in industry, although its share decreases constantly.

The electric power sector has to face important problems:

- lack of capacity reserves in the National Power System;
- ageing of plants; over 10 GW_e have reached the end of their lifetime and this figure will increase by a factor of 4 by the mid 1990s;
- construction of new power plants lasts a lot longer than planned, thus annual capacities actually commissioned are less than needed;
- under public pressure and local authorities decisions, several nuclear, hydro and even thermal power plant projects were canceled.

Table III Electricity generation and consumption

	1970	1985	1988
Installed capacity (GW_e)	166	315	340
Electricity generation (TWh)	740.9	1,544.2	1,705
Electricity consumption by sector: (TWh)			
- industry	488.4	893.6	n.a.
- agriculture	38.6	145.7	n.a.
- transportation	54.4	120.1	n.a.
- residential and commercial	96.0	222.2	n.a.
Distribution losses (TWh)	58.3	133.7	n.a.
Export (TWh)	5.2	28.9	n.a.
Electricity production per capita (kWh)	4,137	5,589	5,960

Primary energy consumption per capita in 1988 was about 5 toe and electricity consumption per capita was about 6 MWh.

2. FUTURE PROSPECTS

2.1 Energy balances for 2000

Transition to market economy has already started in the USSR. This evolution is oriented towards social goals through agriculture development, military industry conversion, modernization, introduction of advanced technologies, energy and natural resources conservation and environmental protection. According to the USSR Government, to overcome the economic crisis the national income has to increase between 1991 and 1995 by 25%, labor efficiency by 29%, industrial production by 20%. A slowing down of the primary energy and raw material production growth is expected, however, mainly due to the decrease of the energy intensity of the national income by 12 to 13% and of the metal consumption by 20%, the growth of demand can be met [6]. It should be noted that this economic growth is quite optimistic; more realistic estimations range from 2 to 3.5% of annual growth rate for the national income (calculated in annual current prices in roubles).

To achieve the targeted economic growth, while limiting the increase of energy demand, dramatic energy savings will be required in different sectors, but this should be possible as a wide range of improvements in energy efficiency and conservation measures may be implemented. Over the past 25 years the GDP energy intensity in the USSR was reduced only by 3.9% while in FRG, USA or Japan it dropped by 18 to 25%. The estimated potential for energy savings in the USSR is about 525 Mtoe per year (almost one third of total energy produced). Out of over 5,000 conservation measures, 70 are considered to be of particular importance and capable of saving 280 Mtoe per year by 2000. All of them are economically beneficial, compared with equal increase of primary energy production. About 140 Mtoe per year could be saved without additional investments. Table IV summarizes the main expected conservation measures and the fuel savings they would entail.

Table IV Conservation measures and expected fuel savings

Conservation measures	Expected fuel savings (Mtoe/yr)
Target-oriented	
- Improvement in industrial furnaces	35
- Higher efficiency in heat supply system facilities and their automation	32
- Use of advanced lighting devices, transformers, variable speed motor drivers, compensators, etc.	35
- Higher contribution of secondary energy resources	14
Miscellaneous	
- District heating	28
- Improvement in metallurgy	49
- Renewal of vehicle stock	14
- Improvements in railway rolling stock	8
- Renewal of aircraft stock	4
- Roads with advanced surfaces	4
TOTAL	223

These measures make it possible to lower considerably the energy intensity of the main industrial sectors. The growth of production in volume, planned by 2000 in the main energy-consuming industries, is several times higher than the corresponding increase in energy demand.

As a result of drastic energy saving measures, the primary energy demand will only be multiplied by a factor of 1.4 to 1.5 between 1985 and 2000, and by a factor of 1.5 to 1.6 by 2010, while the national income will be multiplied by a factor 1.9 to 2 and 3 to 3.5 respectively during the same periods [7].

These conservation measures, corresponding to efficiency improvements, will not cause adverse impacts on social standards neither lower the quality of life.

Electrification of broader areas makes provision for a rise in electricity demand per labor force unit and a wide scale introduction of new technologies using electricity. However, the restructuring of the economy, with priority given to low electricity intensive industries, and the introduction of highly efficient technologies will allow to stabilize, and further on slightly decrease, the electricity intensity of the national income.

Besides, electrification is of great significance for lowering environmental impacts in comparison with a decentralized use of fossil fuels and biomass.

To forecast realistic and rational figures of energy demand and supply, 15 different scenarios were considered by Energy Research Institute (USSR) using simulation models. The basic objectives were as follows:

- labor productivity should be 2.2 to 2.3 times higher in 2000 than in 1985, thereafter the economic growth should remain stable;

- the energy intensity of the national income should fall by not less than 28 to 30% by 2000 and further annual drop by 2.5 to 2.7% is expected, mainly due to energy conservation measures;

- further growth in energy production is to be achieved through higher labor productivity;

- the demand for energy in the residential sector should be completely satisfied, in volume and quality of service;

- environmental control must be provided in the energy and fuel sectors; the specific emission per toe should fall by 23 to 25% in 2000 and by almost 50% in 2010.

Most of the scenarios are based on an annual growth rate of the national income (calculated in annual current prices in roubles) of 5%, while in some cases only a 3.5% growth rate was adopted. The driving parameters of the scenarios are the energy saving rate, electrification, fuel production growth, hydro and nuclear capacities.

Table V shows the USSR energy balances for 1985, 1990 and 2000.

The final energy consumption will increase by 26 to 34%. The increase of the final energy consumption will be 16 to 27% in the industry, 42 to 48% in the transportation sector being mainly due to automobile and aircraft transportation deployment, 44 to 48% in agriculture, and 31 to 42% in the residential and commercial sector. As a result, the share of the industrial sector in the final energy consumption will decrease from 54 to 51%.

The per capita consumption of primary energy in 2000 will be 5.7 to 6.1 toe; for electricity the consumption per capita will be 7,500 kWh. The increase in energy consumption of the residential and commercial sector will result mainly from an increase of the electricity consumption. It is also expected that 40% of the labor productivity rise will be obtained by the deployment of highly efficient electrical techniques in various sectors of the USSR industry.

Table V USSR energy balances for 1985, 1990 and 2000, in Mtoe

Year	Solid fuels	Oil	Gas	Nuclear	Hydro	Electricity	Steam, hot water	Other forms	TOTAL
	1 Production of primary energy								
1985	336	592	532	35	49			42	1586
1990	347	630	679-700	81-60	56			53	1845-1848
2000	420-434	665-644	777-879	133-154	77-81			74-84	2076-2275
	2 Trade balance and change of stocks								
1985	14	158	63	7					242
1990	28-21	180-179	123-102	11					343-312
2000	53-32	143-158	91-158	14					301-378
	3. Consumption of primary energy								
1985	322	434	469	28	49			42	1344
1990	319-329	448-452	557-599	70-49	56			53	1502-1537
2000	368-403	452-466	686-725	119-140	77-81			74-84	1775-1897
	4 Production of electricity								
1985	-91	-56	-88	-28	-49	+98			-214
1990	-(109-116)	-(42-46)	-(95-105)	-(70-49)	-56	+ (112-109)			-(259-263)
2000	-(158-172)	-18	-(84-105)	-(105-126)	-(77-81)	+ (144-165)			-(298-336)
	5. Total final energy consumption								
1985	144	228	137			98	245	11	861
1990	144-147	259	147-158			112-109	273-280	11	945-963
2000	137-144	266-273	175-186			144-165	347-364	25	1085-1155
	5 1. Final energy consumption - industry								
1985	75	56	85			62	179	11	476
1990	76-80	67	76-80			69-66	204-208	11	504-511
2000	67-74	56-60	81-88			84-98	245-263	11	543-592
	5.2. Final energy consumption - transportation								
1985		109				7			116
1990		120-122	6-7			7			133-137
2000		140-144	11			11-14	4		165-172
	5.3. Final energy consumption - agriculture								
1985	9	45	10			10	4		78
1990	11	51-53	11-14			12	6		91-95
2000	18-14	49	21-18			18	7	4-7	116-112
	5.4. Final energy consumption - residential and commercial								
1985	60	18	42			20	62		200
1990	56	21-18	54-57			24	63-67		217-221
2000	53-56	2	63-70			32-35	91		263-280

Fig. 2 shows the evolution of the share of various fuels in the primary energy supply until 2010; it should be noted that the share of nuclear and hydro may be lower. Fig. 3 illustrates the reduction of the national income specific energy intensity. The driving factors of the evolution are the economic restructuring, the shift from energy intensive industry to high-tech and the introduction of advanced production processes in all sectors.

In 2000-2010 thermal power plants, mostly gas and coal-fired, will dominate in the power sector and generate more than 70% of the electricity produced.

Table V shows that a fourfold increase was envisaged for nuclear electricity generation and that the hydro electricity generation would increase by a factor of 1.5 by 2000. These figures seem to be too optimistic taking into account the latest political events in the USSR. Sovereignty acts of several Soviet republics were followed by negative decisions on nuclear development. For instance, Ukrainian Republic (Chernobyl is on its territory) decided to replace nuclear power plants by fossil fuel power plants. The Republic of Russia decided to delay the nuclear program till efficient measures for radioactive waste disposal are worked out. A lot of nuclear projects are canceled elsewhere. In 1989 and 1990 nuclear electricity generation decreased and this trend is likely to continue in the coming 3 to 5 years. Since new hydro projects raise also environmental and social problems, the share of thermal power plants is likely to exceed 75%, rather than being 70% as forecasted by models.

One of the characteristic features of the USSR power industry will still be a large development of district heating and co-generating plants. The share of district heating systems will amount up to 70% in towns and 10 to 20% in rural areas. This will save 28 to 30 Mtoe by 2000-2005, substantially contributing to a better environmental protection [8].

Ecologists are cherishing the hope that unconventional renewables, together with energy conservation, are capable of meeting energy demand. But economic analysis shows that in the next two or three decades the renewables could only be developed to serve local supply in limited areas; their share in the energy supply mix will thus not exceed 2 to 3%.

2.2 Scenarios by 2000-2030

The trends for primary energy resources production by 2030 are shown in Fig. 4 [9]. Again the nuclear power growth should perhaps be reviewed according to the recent trends, although it could be expected that the public acceptation will improve after 2000 when the problems related to safety and waste disposal are solved. Gas production will experience the largest absolute increase and growth rate, followed by coal; oil output will be stabilized at the level of 630 Mtoe and will even slightly decrease at the end of the period.

Hydro potential of the European part of the USSR can be fully utilized by 2010 but no new large hydro power plants can be built in this area. Assuming that the environmental and social acceptance problems will be solved, large hydro plants can be installed in the Eastern part of the country mainly in the mountain regions. At the same time, micro hydro installations have a potential over 500 TWh/year that is expected to be realized partly before and partly after 2000.

Several scenarios have been developed to estimate energy demand and consumption after 2000 [9, 10, 11, 12]. They are the first attempt to reflect in the projections the new economic situation of the country as well as the growing concern experienced worldwide for

CO_2 emissions and greenhouse effects (although no official policy has been adopted in the USSR to deal with greenhouse gases). Three scenarios are briefly presented below:

(**R**) leads to a 20% reduction of CO_2 emissions;

(**E**) is aiming at stabilizing primary energy consumption after 2005-2010, by drastic conservation measures;

(**M**) is a "business-as-usual" scenario, with however some improvements in energy efficiency and substantial restructuring of the industrial sector.

E and **R** are boundary cases not likely to be implemented the USSR economic context even in the post-crisis period. They should be taken only as illustrative of possible paths towards more sustainable futures.

The main results are shown in Table VI and Fig. 5. Due to the inertia of the system substantial changes according to the three scenarios may occur only after 2000-2005. The primary energy consumption will increase by a factor of 1.5 between 1990 and 2030 in the **M** scenario; in the **E** and **R** scenarios, the primary energy consumption will increase by a factor of 1.2 between 1990 and 2005 and stabilize thereafter.

During the next 40 years the energy intensity may decrease by a factor of 2 or 3, relatively slowly before 2005 and faster beyond that date. Per capita electricity consumption will continue to increase from 6.0 to 9.1 or 13.0 MWh.

The CO_2-reduction scenario is characterized by the highest level of electrification and efficiency improvement in electricity generation, a major share, 47%, of hydro and other renewables, a fourfold increase of nuclear capacities, and dramatic achievements in energy savings [11]. In order to achieve significant reductions of CO_2 emissions, changes in the economy and the power industry should start immediately and the present economic situation and system inertia make this process rather doubtful.

Moderate (**M**) and Enhanced (**E**) scenarios will not be able to reduce or stabilize CO_2 emissions, on the contrary they are expected to lead to an increase of the emissions by a factor of 1.4 in **M** scenario and 1.1 in **E** scenario, respectively.

Financial outlook for the 3 scenarios shows that even in **M** scenario additional capital investment will be needed, 4.3% in cumulative GDP in 1990-2030, while for the time being this figure only is about 3.7%. **E** and **R** scenarios give 5.0% and 6.7% respectively, or 1.4 and 1.8 fold increase over the present level.

Table VI Main results of the 3 scenarios [11,12][1]

Indicators	1990	2005	2030		
			M	E	R
Population (million inh)	289 9	324 2	385	385	385
GDP (billion US$)	1670[2]	2420	4490	5720	5720
Annual GDP growth (%)	—	2 5	3.0	3.5	3 5
Primary energy consumption (Mtoe)	1462	1782	2282	1820	1820
Primary energy consumption per capita (toe)	5 0	5.5	6 0	4 8	4 8
Energy intensity (toe/$10^3$$)	0.88	0 74	0.51	0.32	0 32
Energy savings (Mtoe)	—	308	2772	4004	3234
Electricity generation (TWh)	1725 (1800)[3]	2500	3700	3500	5000
Share by source:					
- fossil fuels (%)	73 1	69	62	70	51
- nuclear (%)	13 9	16	24	19	25
- renewables (%)	13	15	14	11	24
Electricity production per capita (MWh)	6 0 (6 2)	7 7	9 6	9 1	13 0
Electricity intensity (kWh/$)	1 03	1 03	0.82	0.61	0.87
Installed capacities (GW_e)	300 (355)	460	710	670	1115
of which:					
- classic thermal	190(252)	270	380	440	415
- nuclear	40(38)	65	125	95	175
- hydro and other renewables	70(65)	125	205	135	525
CO_2 emissions (Mt/yr)	4070	4690	5890	4585	3265
Change in CO_2 emissions compared to 1990 (%)	—	+15	+45	+13	-20
Share of capital investments in fuel-energy sector in cumulative GDP (%)	—	—	4 3	5 0	6 7

Notes. [1] Energy, electricity, CO_2 emissions, saving data are from [11,12], the other figures are from various sources.
[2] According to the most commonly used data
[3] In brackets - expected The authors [11,12] took 1985 as reference year, so the results of 1990 differ from the actual data

3. UNCERTAINTIES

The main uncertainty factor in the energy sector like everywhere in the USSR is the result of the ongoing radical economic reform, which has no historical analogy. The consequences of transition towards market economy, privatization processes, new price policy, including polluter pay principles, conversion of the military industry, and the whole economic restructuring can not be foreseen now clearly. Still the only way out of the critical situation is a highest rate of economic activities in the nearest future.

Moreover, geopolitical changes have become substantial. Having declared sovereignty several republics launched their own economic policies. Changes in fuel policies and electrical infrastructure may be implemented for self-sufficiency and self-financing reasons.

Public opinion becomes more influential and that entails the cancellation of a number of nuclear, hydro and even thermal power plant projects. Public demands are often contradictory and seem even selfish in respect of local interests.

There is no definite public attitude towards CO_2 emission policies, not taking in account declarative support of the necessary reductions. Better knowledge of the problem may transform environmental critique. Ecological situation in the country, improvement of environmental control and new limitations of CO_2 emissions are some other factors of uncertainty.

4. POTENTIALS FOR CHANGE

Beneficial effects of energy conservation, efficiency improvements both on the supply and demand side, especially in the short- and mid- term future are obvious. They will lead to a better economic competitiveness and environmental protection. Institutional changes take place. The USSR Government lately started a long-term program, until 2010, to deal with eight main concerns [1]:

- energy conservation;
- further electrification;
- more effective fuel production;
- rational use of natural gas;
- more effective solid fuel use in thermal power plants;
- completion of the National Interconnected Power System;
- wide use of renewables.

Practical realization of the program envisages construction of cleaner and more efficient power stations, fuel benefication, improved nuclear reactor safety, substantial energy savings in different fields, and so on. This program is financially supported by the Government.

In 1990 the USSR Ministry for Power and Electrification has approved the "Concept of Environmental Protection" by 2005 in the electricity sector. By 2005, the envisaged measures will allow 1.5 time lower harmful emissions, zero discharge, 2 to 3 times higher ash and slag utilization. New policy towards hydro power plants will decrease by a factor of three water area requested per installed kW_e, and by a factor of 10 to 14 the areas taken from the agriculture.

In general fuel-and-power development strategy corresponds to the National Ecological Program by 2005 being under discussion by the Government.

The question is whether new market economy with all of its contradictions during the transition period will be able to support such initiatives. Higher energy prices and market competition will encourage efficiency, as well as new polluter pay principles will stimulate environmentally friendly technology deployment.

5. LIMITS TO CHANGE

Widespread hydro or nuclear deployment looks unlikely until public acceptance could be gained through technological improvement and better communication processes. Improved knowledge regarding the environmental impacts and the means to mitigate them will however facilitate decision-making in the future.

Lack of funding to face large capital investments requested in the energy sector will also limit the possible changes, at least in the short and medium term, subject to the actual economic growth that will be accomplished.

But the most important parameter that could prevent from a coherent policy making process implementation is certainly political and social uncertainty. The decentralization of political power results now in disaggregated decision making, mainly based upon short-term regional analysis. For example, some regional planning favors use of gas for electricity generation rather than efficiency improvements, energy savings or unconventional renewables development. Such policies are driven by local and short-term objectives, and not by global long-term consensus.

The decentralization of the decision making process can also create problems as the National Power System covers most of the country and a failure of one part of it will jeopardize the whole network.

However, there is a hope that present difficulties could be overcome and that an efficient energy policy would be implemented aiming at a sustainable future.

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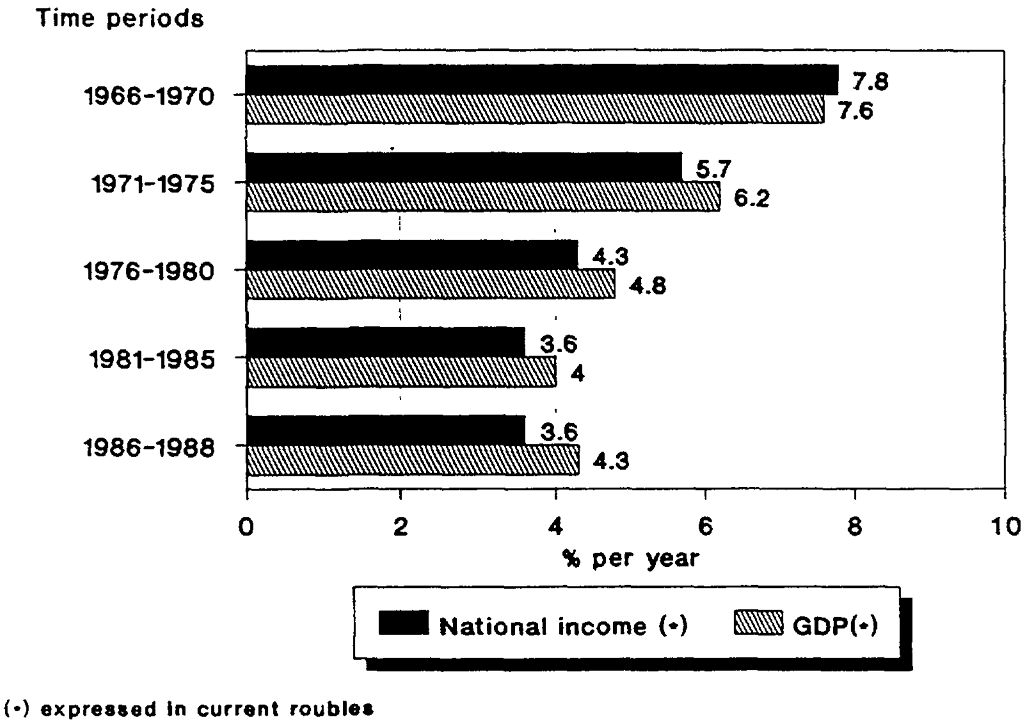


Fig. 1 National income growth rates and GDP growth rates (in the USSR)

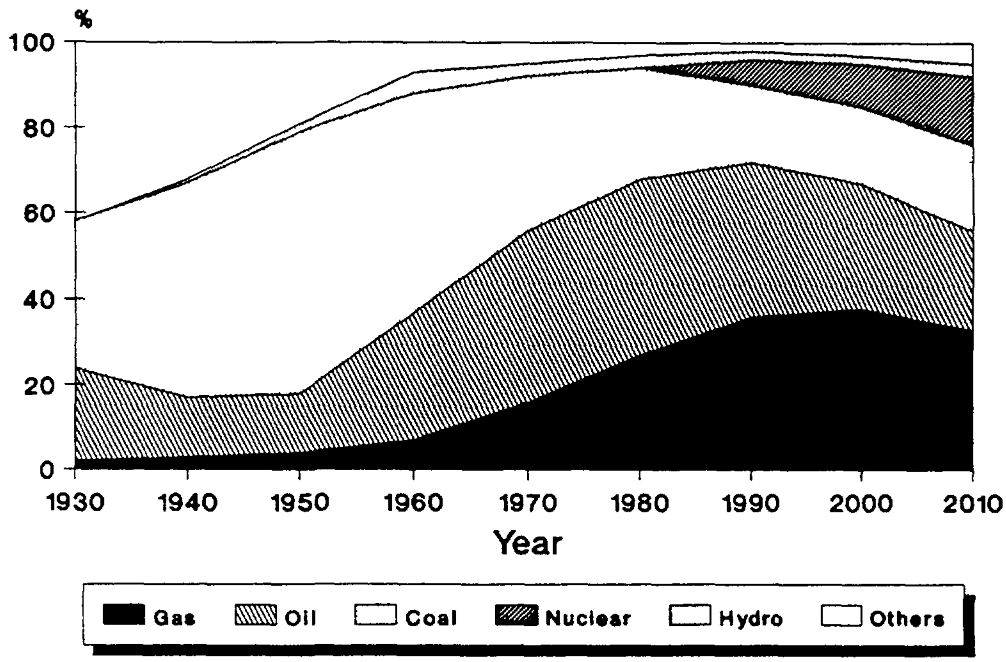


Fig. 2 Primary energy consumption by fuel type

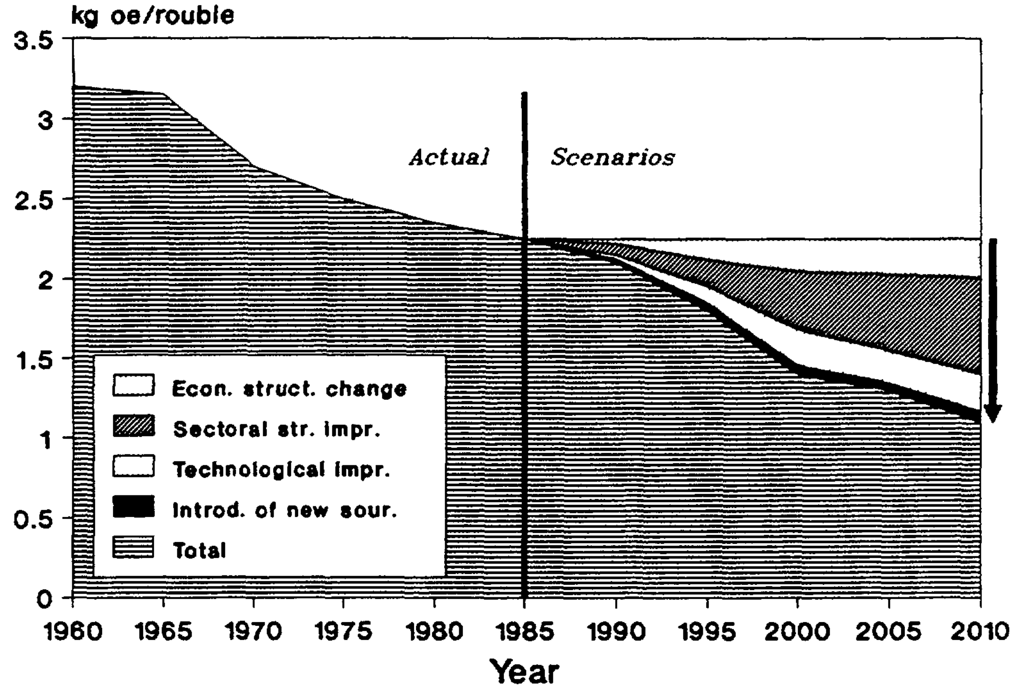


Fig. 3 Impact of different energy strategies on the development of specific energy intensities

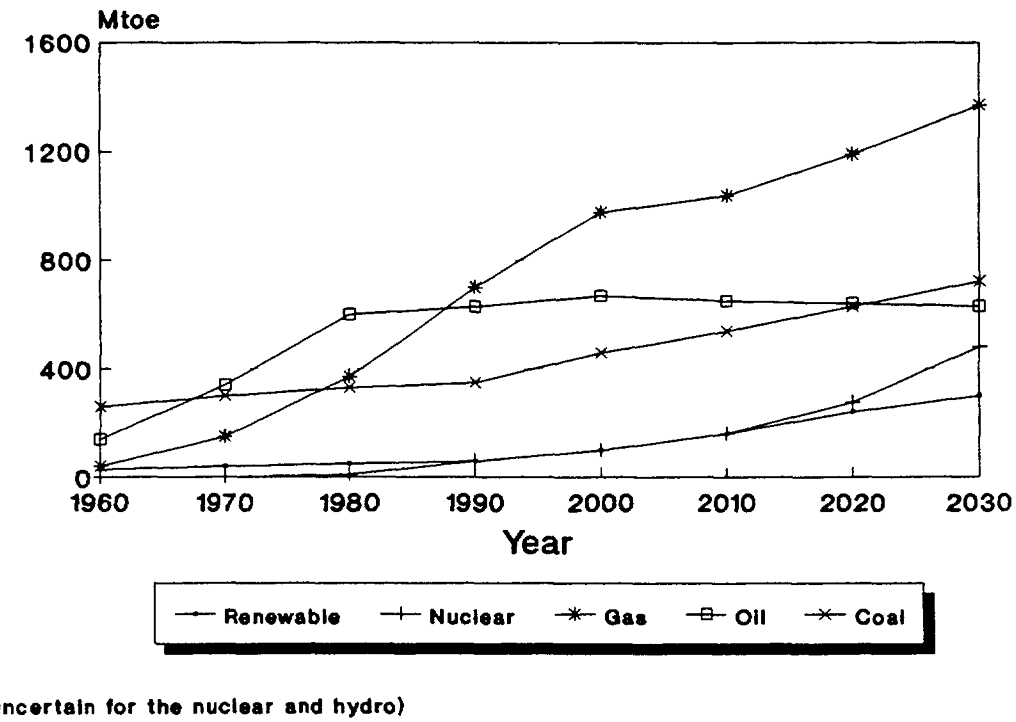
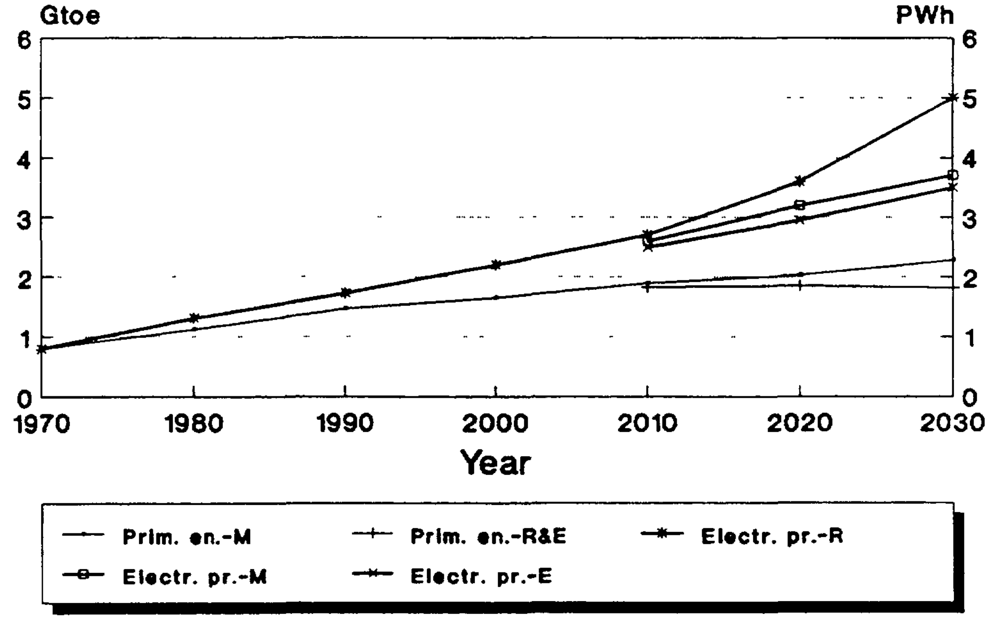


Fig. 4 Historical and projected primary energy production by energy form, 1960-2010

a) Primary energy consumption and electricity production, 1970-2030



(M-moder., E-enhanced, R-CO2 reduction)

b) CO_2 emissions, 1990-2030

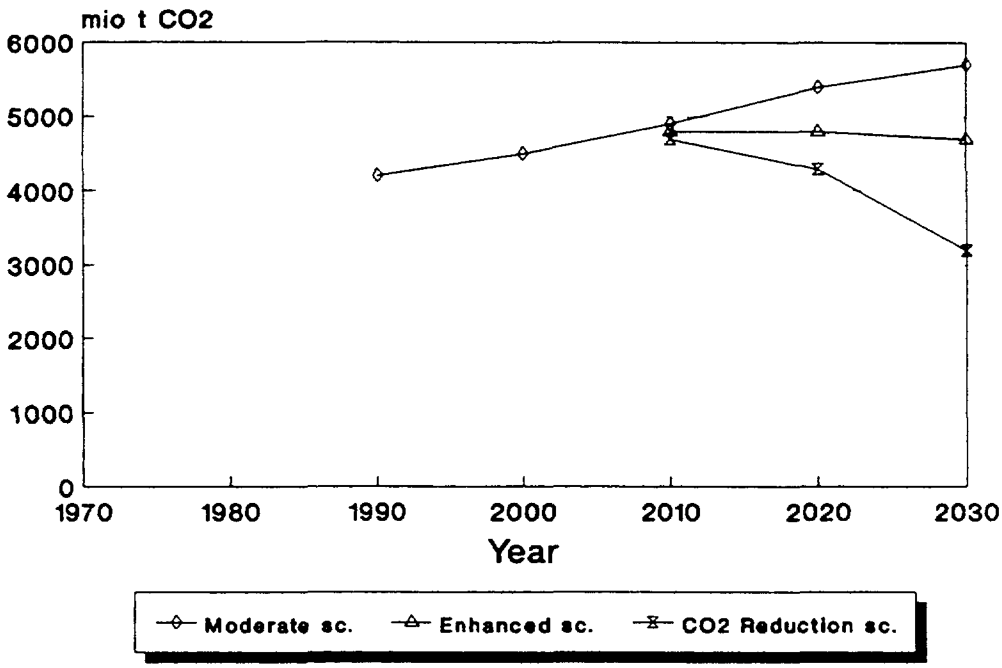


Fig. 5 Results of three energy/electricity scenarios, 1970-2030

INTERACTIONS BETWEEN ELECTRICITY, ENERGY AND THE NATIONAL ECONOMY

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ABSTRACT: Electricity and economic growth are closely linked. For most developed countries the electricity elasticity is in the order of unity, while for developing countries it is generally larger than unity. Energy consumption share for electricity generation in nations' primary energy is one of important indexes of electrification degree in a country. Along with the increasing of this share, the primary energy intensity of the country keeps going down, especially when the share is below 30-35%, so it is of more importance for developing countries.

Although electric power industry in China developed rapidly, the growth rate of the industry did not keep pace with that of national economy in recent years. There exists a wide gap between supply and demand for electricity, so the power development should be hastened to ensure the elasticity factor, at least to equal unity during 1990s. It is necessary to adopt various measures for energy conservation. As a strategical measure for energy conservation, the share of energy consumption for electricity generation keeps going up to make the energy intensity going down.

1. ELECTRIC POWER AND ENERGY RESOURCES IN CHINA

1.1. Present Situation and Recent History

Along with the progressive development of the national economy electricity has become more and more significant for the progress of industry, agriculture and the improvement of the living standards in China. In order to cope with the increasing demands of industry, agriculture and other sectors, the nation's total annual electricity generation increased rapidly during the 1980s by an average growth rate of 7.5%/yr and was 577.5 TWh in 1989. The total thermal and hydro power generation accounted for 461.1 TWh and 116.4 TWh in the 1989, representing 79.8% (71.1% from coal fired, 8.7% from oil and gas fired) and 20.2% respectively. The historical development of total electricity generation and its composition is shown in Table I and Fig 1. It is obvious that the share of oil and gas fired power plants continued its downward trend from 22.9% in 1979 to 8.7% in 1989 while coal fired power plants increased from 59.3% to 71.1% relatively. Hydro power kept its share at about 20%.

Table I Recent History of Electricity Generation and its Composition (1979-1989)

Year	Electricity generation				Growth index		
	Total (TWh)	Hydro (%)	Coal (%)	Oil/Gas (%)	GNP	Primary energy	Electricity generation
1979	281.9	17.8	59.3	22.9	100	100	100
1980	300.6	19.4	59.3	21.3	108	103	107
1981	309.3	21.2	58.7	20.1	113	102	110
1982	327.7	22.7	59.1	18.2	122	106	116
1983	351.4	24.6	59.1	16.3	135	112	125
1984	377.0	23.0	62.7	14.3	155	121	134
1985	410.7	22.5	64.6	12.9	174	130	144
1986	449.6	21.0	68.6	10.4	189	137	159
1987	497.3	20.2	70.4	9.4	210	144	176
1988	545.1	20.0	70.8	9.2	233	157	193
1989	577.5	20.2	71.1	8.7	242		205

By the end of 1989, the total installed generating capacity exceeded 124.5 GW, to which thermal power contributed with 73.0% (90.9 GW) and hydro power 27.0% (33.6 GW) respectively.

Up to now, 22 power grids with different sizes have been formed throughout the country and the generating capacity already connected into grids is up to 86% of the nation's total. There are 8 large sized power networks each with a capacity of 7,000 MW and above, namely, Northeast, North China, East China, Central China, Northwest, Southwest and South China regional power networks, as well as Shandong Provincial Network, of which the capacity of the first four networks exceeds 18,000 MW each. The distribution of power networks and their service areas is shown in Fig. 2 and Table II.

In recent years, electricity consumption has increased its share in various sectors as well as in the whole primary energy mix. Total electricity consumption increased from 233.6 TWh in 1979 to 499.5 TWh in 1989, which represents average growth rate of 7.9%/yr. The shares of electricity consumption by various sectors were as follows: industrial sector 71.8% (57.3% for heavy industry and 14.5% for light industry); rural consumption 16.4%; municipal and residential consumption 9.9%; and 1.9% for the transportation sector (see Table III and Fig. 3).

Table II Distribution of Installed Capacity and Electricity Generation in Several Regional Networks and Other Provincial Grids in 1989

Network & Region	Installed capacity		Electricity generation	
	Total (MW)	Share hydro (%)	Total (TWh)	Share hydro (%)
Northeast Power Network	19210	18.0	84.3	17.1
North China Power N.	18590	4.6	87.9	1.9
East China Power N.	20280	11.6	86.0	6.2
Central China Power N.	17940	39.5	74.6	41.0
Nortwest China Power N.	7860	49.5	39.5	41.2
Southwest China Power N.	6910	39.2	30.9	33.6
South China Power N.	8380	40.2	26.4	21.9
Shandong Provincial Grid	7350	0.7	37.8	
Fujian Provincial Grid	2920	43.2	10.3	42.0
Yunnan Provincial Grid	2330	55.4	8.3	40.3

Table III Electricity Consumption by Various Sectors as a Share of Total Electricity Consumption since 1949

Year	Total China (TWh)	Industry			Transportation (%)	Rural (incl. housholds) (%)	Municipal & Res. (%)
		Whole (%)	Heavy (%)	Light (%)			
1949	3.5	69.1	34.4	34.7	0.6	0.6	29.8
1952	6.2	80.0	43.0	37.0	0.9	0.7	18.4
1957	16.4	82.9	58.6	24.3	0.4	0.7	16.0
1962	37.8	84.6	70.0	14.6	0.6	4.1	10.7
1966	70.0	84.1	69.1	15.0	0.6	7.8	7.5
1972	123.6	82.3	69.7	12.6	0.6	10.5	6.6
1976	164.7	78.3	64.6	13.7	1.1	14.1	6.5
1977	186.3	78.5	65.0	13.5	1.2	13.7	6.6
1978	214.9	79.0	65.9	13.1	1.1	13.7	6.3
1979	233.6	79.0	65.9	13.1	0.6	13.9	6.5
1980	251.6	77.9	64.5	13.4	0.6	14.9	6.6
1981	259.0	76.2	62.6	13.6	0.8	16.0	7.0
1982	275.3	76.0	62.0	14.0	0.7	16.0	7.6
1983	297.1	75.7	60.9	14.8	0.7	16.0	7.6
1984	319.6	75.2	60.5	14.7	0.8	15.9	8.1
1985	348.5	73.8	58.8	15.0	0.9	16.5	8.8
1986	379.7	72.9	57.7	15.2	1.2	16.4	9.5
1987	423.5	72.5	57.9	14.6	1.2	16.4	9.9
1988	461.3	71.8	57.3	14.5	1.9	16.4	9.9

Adopting various measures for energy conservation and increasing the share of energy for electricity generation in total primary energy, the energy consumption per unit output value (energy intensity) decreased. Indexes at 1980, the energy intensity was down to 1.46 kgce (coal equivalent) per US dollar in 1988 from 2.09 kgce in 1980, while the share of electricity in the total primary energy increased from 18.6% to 22.8% during the same period (see Table IV). The primary energy consumption and mix is shown in Table V. The total primary energy consumption amounted to 920 Mtce in 1988, representing an average yearly growth rate of 5.1% during 1980s, in which the share of coal keeps increasing from 71.31% of 1979 to 76.10% and the share of oil and gas is going down relatively, whilst the share of hydropower showed a minor increase.

Table IV The Trend of Energy Intensity with Growth of Electricity Share

Year	(1.) GNP (billion US$80)	(2.) Primary energy (Mtce)	Share of electricity (%)	(2.)/(1.) Energy intensity (kgce/US$)
1980	289.1	602.75	18.6	2.09
1981	302.3	594.47	19.4	1.97
1982	328.7	626.46	20.1	1.91
1983	361.6	660.40	20.7	1.83
1984	414.8	709.04	21.2	1.71
1985	468.6	770.20	21.1	1.64
1986	507.6	816.65	21.9	1.61
1987	561.4	859.43	22.4	1.53
1988	628.7	920.00	22.8	1.46
2000	1265.0	1400.00	32.1	1.12

Table V Primary Energy Consumption and Mix (1979-1988)

Year	Total consumption (Mtce)	Share of resources			
		Coal (%)	Crude Oil (%)	Natural Gas (%)	Hydroenergy (%)
1979	585.88	71.31	21.79	3.30	3.60
1980	602.75	71.81	21.05	3.14	4.00
1981	594.47	72.74	19.92	2.85	4.49
1982	619.37	73.92	18.67	2.56	4.85
1983	656.48	73.70	18.50	2.50	5.30
1984	707.32	75.10	17.70	2.30	4.90
1985	764.26	75.85	17.09	2.25	4.81
1986	816.65	76.07	17.03	2.24	4.66
1987	859.43	76.27	16.99	2.15	4.56
1988	920.00	76.10	17.10	2.10	4.70

Notwithstanding the development of energy industry with rapid growth of electric power, the growth rate of the industry did not keep pace with that of national economy in recent years. By analyzing the trend of electric power industry and GNP during past ten years (see Fig. 4), the annual average growth rate of electricity production (7.5%) was quite lower than that of GNP (9.5%), whilst the growth rate of primary energy consumption was only 5.1%. Hence there exists a wide gap between supply and demand for electricity and primary energy, of a nationwide nature. As a matter of fact, the gap is going up to 15-18 GW for installed generating capacity and 75-90 TWh for annual generation by rough estimate.

1.2. Outlook and Strategy

In order to meet the demand of quadrupling the gross national product value for electricity to the year 2000, as compared to 1980, developments in the electric power sector should be speeded up to ensure the elasticity factor approaching unity at least. Such development would imply an average growth of 6%/yr.

The nation's total installed capacity will be 240 GW by the end of this century and annual electricity generation will amount to 1,200 TWh. For further development within the time span 2000-2015 and to keep in step with the national economy development, the total installed generating capacity and electricity generation should reach 480 GW and 2,400 TWh, implying an average growth rate 4.7%/yr. To support the development plan, the total primary energy production will have to equal to 1.43 billion tons of standard coal by the year 2000, which includes 1.4 billion tons of raw coal, 200 million tons of crude oil, 30 billion cubic meters of natural gas, 90 million tons of coal equivalent of nuclear power, so as to ensure the energy elasticity factor, at least, to equal 0.5, representing the average annual growth rate over 3.7%. The primary energy consumption mix will have a change as follows: the share of coal will decrease to 70% (1988: 76.1%), whilst the share of oil and natural gas will increase to 22.8% (1988: 19.2%); hydropower and nuclear share will be 6.3% and 0.9% respectively.

For realizing the targets mentioned above, the energy industry will be developed with electric power as its kernel and based on coal. While speeding up capital construction of energy industry and electric power, equal stress has been laid on opening new resources and cutting down expenditure, planned energy consumption, energy conservation as well as reduction of unit energy consumption rates are all of importance. As a strategic measure for energy conservation, the share of energy consumption for electricity generation in the total primary energy should be increased to 32% by the end of this century so as to make the energy intensity going down to 1.1 kgce per US dollar in 2000 from 1.5 kgce per US dollar in 1988 (see Table IV), with adopting other energy conservation measures. It is a key problem to keep the balance between supply and demand for primary energy and electricity during 1990s.

According to the situation of primary energy and its development strategy and considering the financing conditions, the thermal power based on coal fired will still be the main power for meeting the electricity demand and the share of the thermal power in the total electric generation will keep 75-77% during 1990s owing to its lower capital cost and shorter construction period. The new-added thermal power units will be coal fired principally and the oil-fired power plants will no longer be constructed generally because the oil is also valuable chemical raw materials. The policy will make the share of coal fired power in total electric generation being 71-73% and share of oil and gas fired power only 4-5%. By the end of the century, the total thermal installed capacity will go up to 160 GW, representing the share of thermal power in total installed capacity being 67% (63-63.5% for coal fired and 3.5-4% for oil and gas fired). The structure of generating capacity and electricity generation by fuel type to the year 2000 is shown in Fig. 5. The share of the hydropower will be 30% and 20% for capacity and electricity generation respectively, and the share of the nuclear power will be 2.5-3% and 3-3.5% relatively.

1.3. Environmental Impact

Along with more numerous coal fired electrical power plants put into operation, the issue of environmental impact is becoming more serious gradually. It is estimated that by the year 2000 the annual electricity generation from coal fired plants will amount to 900-920 TWh. For this amount of electricity the raw coal consumed will be in the order of 0.45-0.46 billion tons representing the share of coal consumption in total output being 32-33%, therefore the particulate emission from coal fired power plants will be more than 6 million tons per year, basing upon the status quo technique of dust removal, and the SO_2 emission more than 7.5 million tons per year.

It is a very hard task for environmental protection as most of the coal fired power plants are relatively concentrated in more industrialized areas with more dense population. The priority is given to flue dust emission control, the solution of the ways to decrease the particulate emission which has exceeded the state allowable limit is particularly to be stressed. Eventually the particulate emission from all of new power plants (i.e. 100% of them) commissioned in the 1990s will have to be below the emission limits and 90% of presently operating power plants will have their emission below the limits. To reach such a goal, it would be absolutely insufficient by relying solely upon the measures taken with high rise chimney (180-240 m high), high efficiency precipitator (or 99.5% efficiency) and by burning low ash and sulphur contents coal. Though it is estimated that the average dust removing capability of all the thermal power plants in the nation will reach 96% by the year 2000, it is necessary to develop advanced equipments for purifying flue gas.

As the sulphur content of coal fired in our country is in the range of 0.2-6% and about 25% of the coal with a sulphur content 2%, for newly built large capacity power plants in the regions burning high sulphur content coal, it is imperative that up to date flue gas scrubbers should be adopted and the fluidized bed combustion technique be promoted. Currently, various processes of flue gas desulfurization are being under testing, such as the lime-gypsum, the sodium sulfite, the activated carbon absorption and the wet scrubbing processes, and preliminary results have been attained. It will be put into commercial operation and get wide promotion in the near future.

Besides, we are promoting the composite utilization of boiler coal ash in conjunction with environmental protection, such as used as additives of cement formation, brick making, etc. It is estimated that the quantity of ash thus utilized will amount to 30 million tons, being about 24% of total ash formation from power plant boilers.

1.4. Potentials for rational use of energy

1.4.1. Improving the efficiency of thermal power generation

As mentioned above the coal consumption by thermal power plants will share 32-33% of nation's total coal output by the year 2000, so it is significant to improve the efficiency of thermal power generation as one of the measures for energy conservation and environmental protection. For this purpose, stress will be focused on the construction of large power plants each with a capacity of 1,200-2,400 MW in pithead of huge coal mines and economically developed coastal districts as well as in the vicinity of load centers.

The new thermal power plants to be constructed during 1990s will be equipped with large sized high temperature and high pressure efficient units, such as 200 MW, 600 MW and larger sized units. By the end of this century, 300 MW and 600 MW units will become the main force in thermal power field.

While making efforts to develop large sized units, the priority is also given to medium and small co-generation units. It is planned to construct medium and small co-generation units with a total capacity of 10,000 MW in coming five or seven years. Besides, the stress will be laid on the renewal and retrofit of old generating units with a total capacity of 14,000 MW commissioned during 1950s and 1960s. It is anticipated that the average generation efficiency in thermal power field will be improved from 31% of 1988 up to 35-36% in the year 2000, corresponding to saving 60 million tons of raw coal for generating 900 TWh in coal fired power field.

1.4.2. Exploiting more hydropower to increase its share in the total electricity generation

Hydropower resources are very abundant and play an important role in China's power industry. According to the latest survey, the theoretical hydro-potential is 676 GW, of which exploitable potential totals 378 GW. In recent years, the hydropower contributes about 30% and 20% to the total generating capacity and electricity generation respectively. At present, however, the hydropower installed capacity, together with the capacity under construction, is less than 15% of exploitable potential.

This situation means that efforts should be concentrated on continuous exploitation of some river sections with abundant potentials and favorable conditions. The key points for hydropower exploitation in the coming years should be to develop the water resources of the upper and middle regions of Changjiang River, upper regions of Huanghe River as well as Hongshui River basin for speeding up hydropower expansion. Meanwhile, a feasibility study for the renowned Three Gorges Power Station and its preliminary design is now underway.

It is planned that the new-added installed capacity during 1990s will be 40 GW and keep the hydropower capacity and electricity generation being 30% and 20% of nation's total (scenario I).

The key issues of limiting hydropower exploitation are its higher capital cost and longer construction period, as compared with thermal power, especially under the situation of power shortage and investment shortage for the time being in China. In order to open new channels to finance the more projects, it is necessary to reform original investment system. A joint investment system of the central government, local government and large enterprises has been introduced, instead of relying solely on central government. For supplement the deficiency of funds, utilization of foreign funds has been promoted and will be further extended in the coming years. It is expected that the hydropower share will be able to increase to 37% and 25% (scenario II) in the nation's total capacity and electricity generation of the year 2000 respectively, as a result of financing more hydro power projects and exploiting more medium sized stations.

1.4.3. Embarking on development of nuclear power

Due to shortage of coal deposit and hydropower in Northeast China, East China and Guangdong Province, it is in urgent need to build nuclear power plants, as a supplement to thermal and hydropower, to meet the continuously increasing load-demand and to gain experience in further developing nuclear power. At present, the first nuclear power plant --- Qinshan Plant with 300 MW of capacity is under construction.

This plant will be provided with PWR reactor made in China and is expected to come into operation by 1990. After that, it will be expanded by two 600 MW PWR units. In addition, the Guandong Nuclear Power Joint Venture Company was formed in 1985 and is in charge of building Daya Bay Nuclear Power Plant with two 900 MW PWR units, the nuclear island of which is provided by France and the conventional island by the United Kingdom.

The plant will be put into operation in 1992. The total nuclear power installed capacity will be 6,000-7,000 MW by the year 2000 and take the share 2.5-3% in the nation's total. It is anticipated that the share of nuclear power will increase to 5% and 7% in the nation's total capacity and electricity generation respectively to the year 2015.

1.4.4. Opening new renewable energy resources

While making efforts to develop conventional energy resources, opening new renewable energy resources for power generation has been encouraged. Several kinds of renewable resources such as small hydro, wind, tidal, solar and geothermal power have been developed in accordance with local energy resources conditions.

Among these resources small hydropower is the most realistic and has played an important role in developing rural production and improving livelihood. Up to now, more than 70,000 small hydropower plants (12 MW and below) have been built with a total installed capacity of about 10,000 MW spreading over 1580 counties. It is expected that the total capacity of new-added small hydropower during 1990s will be 8,000 MW. Several tidal power plants, generally with an installed capacity of 40-640 kW have been build up. A pilot geothermal power plant has been built at Yangbajing, Tibet with a total capacity of 13 MW. More than 50 types of small-medium sized wind power equipments of various capacities have been developed, which are mostly located in the remote areas, the coastal islands and pasture-areas far from the networks.

2. ROLE OF ELECTRICITY IN NATIONAL PLANNING

2.1. Energy Elasticity and Electricity Elasticity

In the case of a country for transforming from with agriculture as main economical trunk to with industry as main one, the demand of energy is bound to increase at the same time with the national product due to the energy intensive heavy industry and fundamental facilities which are continuously founded and put into operation.

Take for instance the case of countries of the Organization for Economic Co-operation and Development (OECD); before 1973 these two were closely related. While after that year owing to the fact that the mode of energy consumption of those countries altered by resorting to new technique to speed up technical improvements, by changing the structure of consumption, by shifting such energy intensive industry as raw materials exploitation and processing to developing countries, etc., the mutual influence between the primary energy consumption and national production gradually shrunk.

As for the developing countries, where the fundamental industry facilities which are needed to develop their own national economy are to be constructed and widely utilized non-commercial energy in rural districts are gradually substituted by commercial energy, there is a great potential for energy consumption.

Table VI shows the growth rates of national economy and energy consumption of countries together with historical data and long-range forecast of corresponding energy elasticities. It is readily seen that although the energy elasticities of industrialized countries have dropped to between 0.1 to 0.4, those for developing countries still remain in the range of O.7 to 1.0.

Table VI Average Annual Growth Rates of Gross National Product and Energy Elasticities for Developed and Developing Countries

Scenario	1965/1973	1973/1980	1980/2000 I	1980/2000 II
Growth rate of GNP (%, fixed rate)				
OECD countries	4.7	2.8	2.0	3.0
Developing countries	6.6	5.5	3.5	4.5
P.E. countries	-	-	2.8	3.8
Growth rate of primary energy consumption (%)				
OECD countries	5.2	1.1	0.1	1.3
Developing countries	6.6	4.5	2.5	4.7
P.E. countries	4.7	3.0	1.8	2.3
Energy elasticities				
OECD countries	1.1	0.4	0.1	0.4
Developing countries	1.0	0.8	0.7	1.0
P.E. countries	-	-	0.7	0.6

In utilization of low quality fuel, nuclear energy and various renewable energy, electricity, a secondary energy, is the only one that can be generated in large scale to substitute the requirement of high quality fuel, such as fossil oil, natural gas, coke, etc. In being end used, it can be used more directly than energy in other form, thus it possesses incomparable superiority. Consequently the rate of electricity consumption is always, higher than that of all energy consumption and the growth rate of electricity generation should be higher than that of the exploitation of primary energy.

For most developed countries, the electricity elasticity is in the order of unity, while for developing countries, generally it is larger than unity, in spite of the fact that in certain short period, there may be some fluctuation of electric elasticity as a consequence of economical structure adjustment and execution of effective energy and electricity conservation policies in some countries.

2.2. Effect of Electrification Degree on Energy Intensity

Energy consumption share for electricity generation in nation's total primary energy consumption is one of important indexes of electrification degree in a country. It corresponds to the development level of national economy. The growth of energy consumption share of electricity always increases in line with that of GNP. During the 1960s in USA, USSR and major Western European countries, this share was in the range of 20-25%, but exceeded 25% in the 1970s and over 1/3 in the 1980s. It is expected that this share will increase to 40-45% in these countries (Table VII).

Table VII Share of Primary Energy Consumption for Electricity Generation in Selected Countries

	1960	1970	1980	1985	2000
China	12.5	17.2	18.6	21.1	30
United States	18.7	24.7	32.5	34.1	45
USSR	26.5	32.3	33.3	33.3	
Japan	25.0	25.4	33.0	35.0	40
West Germany	22.0	25.0	33.6	35.6	40
Canada	31.4	37.8	44.7		47
France	21.0	22.0	32.2	39.1	42
Great Britain	24.0	31.4	34.7	35.0	39
Brazil	28.8	36.9			
India	21.9	28.6			

For developing countries such as Mexico, Brazil, Egypt, South Korea, India, the Philippines, etc., the share was below 20% in the 1970s. When it came to the 1980s, the share of most of them reached 20% and in many countries it has even exceeded 25% currently.

As mentioned in section 1, the energy consumption share for electricity generation in China increased steadily with the growth of GNP, from 12.5% of 1960s to 18.6% of 1980, with further increasing to 22.8% in 1988. Along with the increasing of this share, the primary energy intensity of the country kept going down. During 1980s the energy intensity decreased from 2.09 kgce per US dollar in 1980 to 1.46 kgce per US dollar in 1988, based on the fixed rate of 1980.

From the statistic data of the world there is a close relationship between the energy consumption share for electricity generation and the value of energy intensity, which is true also for China. With electricity, which is transformed from primary energy used, the utilization efficiency of energy can generally be improved, thus rendering the total quantity of primary energy consumed be conserved. By analyzing the data of 100 countries and districts with per capita GNP of 300 US dollars and above, a statistically strong relationship can be found, i.e. with the energy consumption share for electricity generation being below 20%, the energy intensity would be well above 2.0 kgce per US dollar and with the share going up to 30%, the energy intensity can drop down to the order of 1 kgce per US dollar (Table VIII).

For developing countries to analyze the effect of energy consumption share for electric generation upon the energy intensity is more important.

It can be seen from Fig. 6 that the reduction of energy intensity with the elevation of this share is more significant when the share is less than 30-35%, which is generally the value of developing countries. In other words, it is especially important for the developing countries whose electricity share is low, to develop electric industry and to promote the degree of electrification. Thus the energy intensity can be effectively reduced and consequently it is advantageous for energy conservation and environmental protection.

Table VIII Energy Intensities/Share of Energy Consumption for Electricity

Countries	Share for electricity in total primary energy (%)			Energy sector (kgce/US$80)		
	1973	1980	1985	1973	1980	1985
USA	26.5	32.5	34.1	1.09	0.97	0.84
UK	32.7	34.2	35.0	0.63	0.54	0.50
FRG	28.0	33.6	35.6	0.54	0.49	0.44
France	23.5	32.2	39.1	0.47	0.43	0.40
Japan	30.2	33.0	39.8	0.59	0.49	0.41
Canada	32.7	37.8	42.7	1.26	1.17	1.11
Italy	24.0	-	28.8	1.89	-	0.70
Austria	29.0	34.4	38.7	1.72	0.50	0.47
Switzerland	-	-	44.7	-	-	0.36
Spain	-	35.4	40.5	-	0.49	0.47
Finland	-	34.1	40.8	-	0.73	0.66
Sweden	-	-	48.0	-	-	0.64
Australia	-	36.2	38.6	-	0.71	0.66
Chile	-	31.7	37.5	-	0.79	0.67
Brazil	-	28.8	36.9	-	1.20	0.96
Argentina	-	22.7	29.3	-	1.12	0.94
Mexico	-	19.5	30.9	-	1.27	0.89
South Korea	-	16.1	25.2	-	1.86	1.17
Philippines	-	25.6	27.1	-	1.36	1.13
India	-	21.9	28.6	-	1.43	1.29
Egypt	-	26.9	32.5	-	1.23	1.12
USSR	-	33.3	34.2	-	0.9	0.86
Yugoslavia	-	-	30.5	-	-	1.29
Poland	-	23.9	-	-	1.3	-
CSFR	-	30.0	-	-	1.1	-
Hungary	-	26.8	-	-	1.9	-
GDR	-	30.1	-	-	1.0	-

This is more marked for environment protection where coal plays a major role in the primary energy. The reason why the energy conservation effect is evident when the energy consumption share for electricity generation is comparatively low is that electricity consumed by industrial sector generally accounts for the major part, the increase of electricity consumption will be mostly devoted on industry to render the utilization effect materially improved. While after energy consumption share for electricity generation exceeding 30-35%, a large part of further increase of electricity consumption will be devoted to commercial and residential sectors which make the effect not so obvious. After all, a conclusion can be drawn that the increase of electricity (secondary energy) consumption share is beneficial for energy conservation as well as for environmental protection.

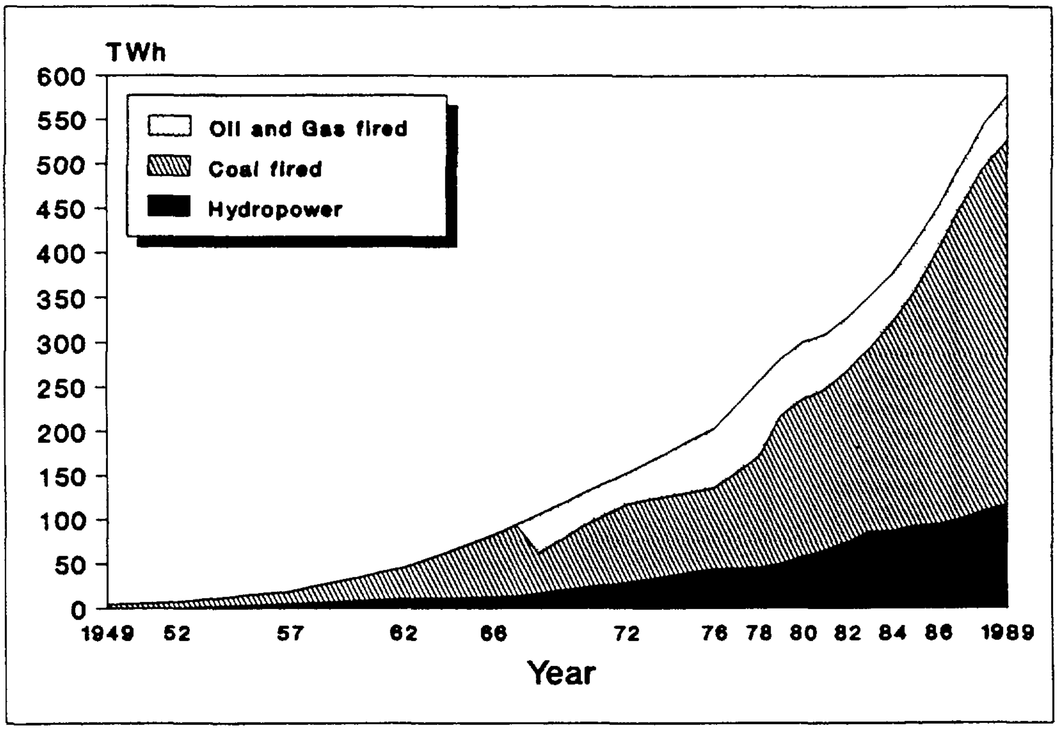

Fig. 1 The Historical Development of Total Electricity Generation and its Composition since 1949

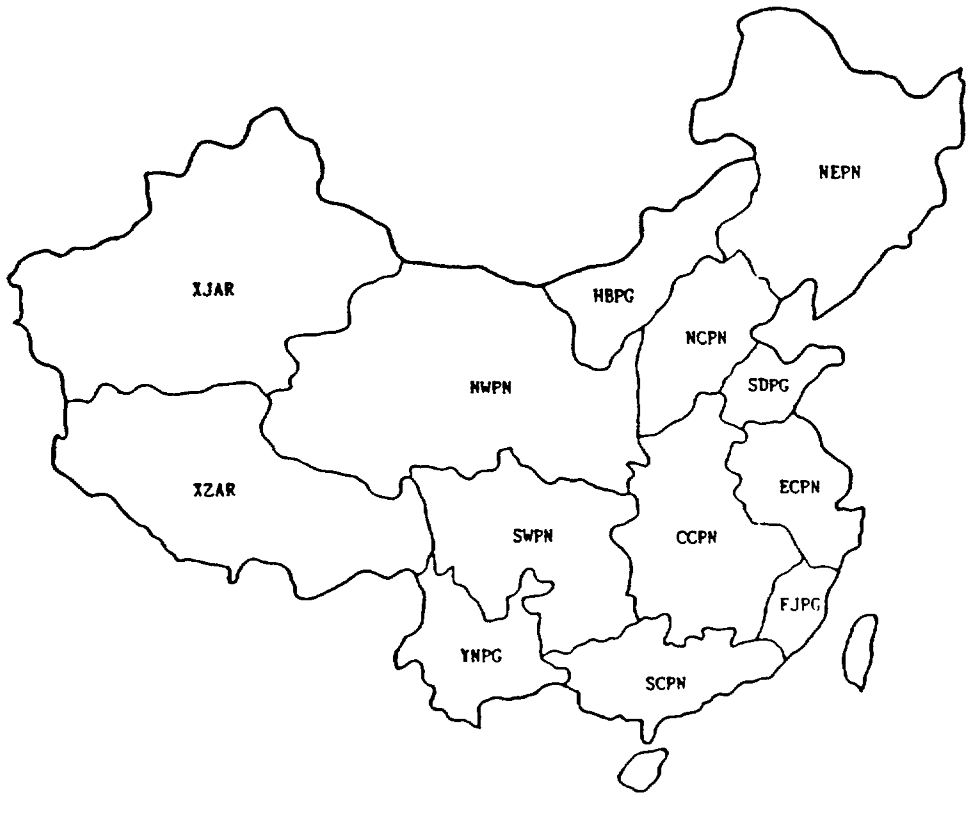

Fig. 2 Distribution of Power Networks

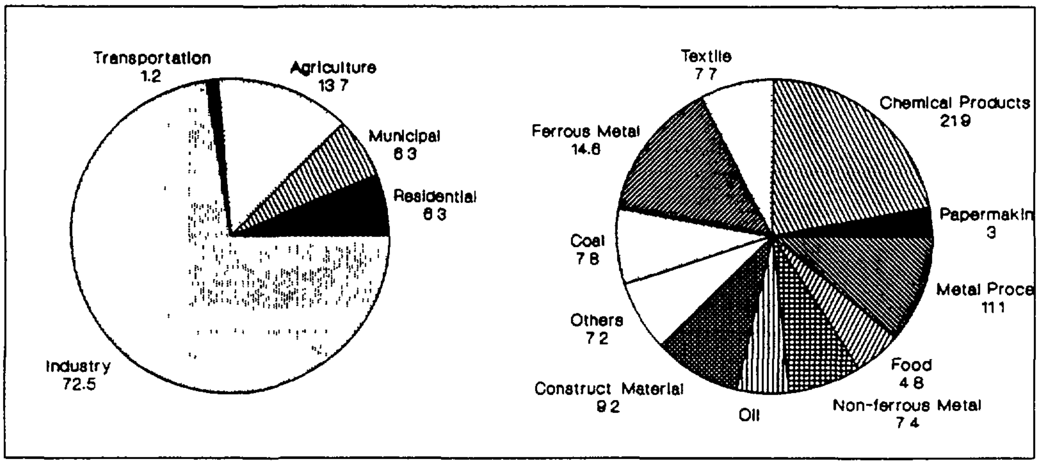

Fig. 3 Electricity Consumption Structure

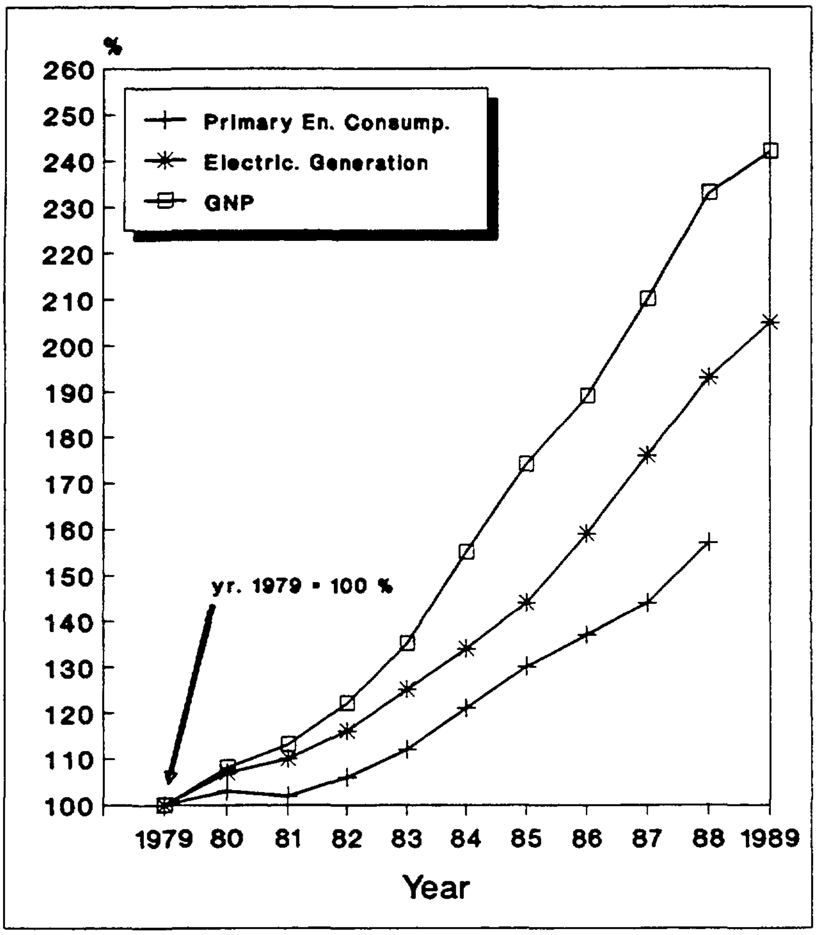

Fig. 4 The Historical Development of Electricity Generation, Primary Energy Demand and GNP, (1979-1989) 1979=100

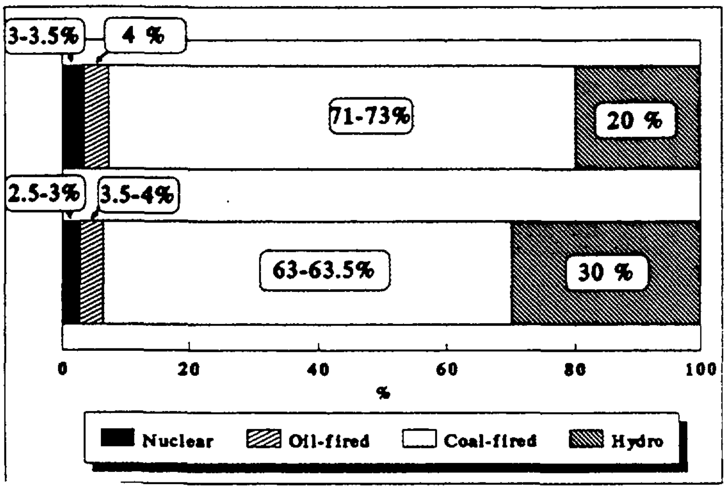

Fig. 5 Composition of Electric Generation and Installed Capacity in the year 2000

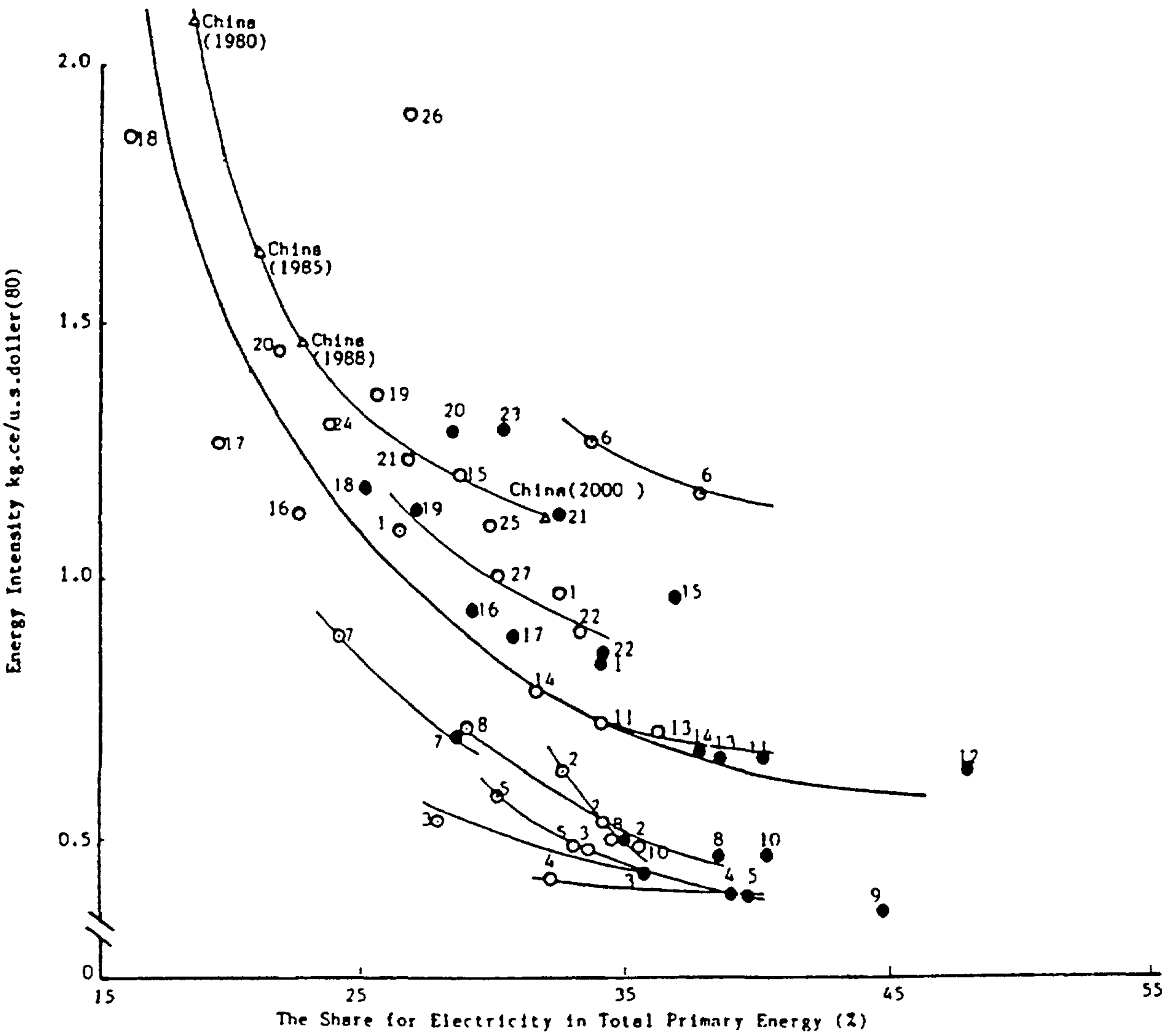

Fig. 6 Energy Intensities Versus Shares of Energy Consumption for Electricity

THE LDC POWER SECTOR:
A BRIEF OVERVIEW AND GLOBAL OUTLOOK

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ABSTRACT: Notwithstanding the deteriorating performance of the LDC' power sector, the generating capacity is planned to increase by more than 80% over the next decade. Sector expansion will heavily rely on coal thermal additions and the development of hydropower resources. Environmental concerns aside, the shortfall of finance is likely to become the major obstacle to sector growth. Capital constraints, the urgent need to upgrade and reinforce the existing structure, as well as the implementation of overdue institutional reforms most probably will result in a considerable slow-down of the envisaged expansion programs.

1. BACKGROUND

In LDCs, the power sector's quantitative impact on national energy balances is still rather low, notwithstanding the fact that huge efforts have been taken to foster power sector development. While in Western Europe and North America electricity accounts for about 16% of total final energy consumption (1987-figures that compare to a share of 11% in 1973), power generation in LDCs on average contributes significantly less than 10% to final energy use. In most Sub-saharan countries the share of electricity in final energy consumption has not even reached the 1%-level.

On a per-capita basis, the role electricity plays in LDCs is modest as well. While the OECD countries' average per capita consumption of electricity is in excess of 8,000 kWh a year, the LDCs' annual consumption works out at 625 kWh per capita. Almost one third of the developing countries consume less than 100 kWh per capita and year; and in sixty LDCs (out of a sample of 96) annual per capita consumption falls short of the 500 kWh-level [3].

Even though in many LDCs the ratio of electricity consumption to GDP is considerably below the level that persists in the developed world, in 1987 the developing countries' average electricity intensity amounted to 56 kWh per UScent of GDP, and thus, was roughly in line with the figure recorded for North America. While the aggregate electricity intensities of Western Europe and North America remained almost constant from 1973 to 1987 and are not likely to change over the next decade [11], in the LDCs, though, the trend is for a markedly higher use of electricity per unit of GDP, irrespective of whether or not the countries will succeed in achieving substantial improvements in electricity end-use efficiency.

There is a strong country-specific streak in the sectoral composition of electricity consumption. Electricity use by sector is particularly erratic in low-income countries where the presence or absence of a few, large consumers may dominate (flaw) the picture. In higher-income countries the electricity consumption pattern tends to resemble more closely the sectoral structure of demand prevailing in the developed world, but in the former this pattern is associated with a much higher electricity intensity. Moreover, "excessive" levels of electricity consumption per unit of GDP either correlate with large shares of electricity accounted for by industry and agriculture (e.g. China, Zimbabwe, India) or reflect a strong bias towards residential demand (e.g. Colombia, Dominican Republic).

Care should be taken in assessing the economic potential for improvements in electricity end-use efficiency. While a relatively high electricity intensity clearly indicates that savings are technically feasible, only part of this potential may be economically accessible in the short- to medium-term. Where capital is required to substitute for energy, the developing countries' comparative advantage in trade may rest on the use of energy-intensive technologies. Also, for countries stuck with durable equipment the costs of which are sunk, energy savings alone may not justify immediate investments in new, less energy-intensive facilities. So the scope for energy/electricity conservation in the short-run may significantly differ from the savings potential that can be captured in the long-run.

Given the LDCs' low level of electricity use and taking into account that additional GDP growth, accompanied by technological, inter-, and intra-sectoral changes, as well as the achievement of a higher standard of living call for more versatile forms of energy, electricity demand is likely to increase sharply. In fact, unlike the developed world where electricity growth by and large has approximated the growth in GDP, the elasticity that electricity consumption in LDCs has with respect to GDP tends to be greater than unity, and in some countries the use of electricity has grown more than twice the rate of GDP. On average, the LDCs annual rate of growth in electricity consumption was 10% during the 1970s and 7% during the 1980s, while average annual GDP growth fell from 4.1% in the period 1965-80 to 3.1% between 1980 and 1988 [10]. For comparison, in the period 1973 to 1979 the IEA countries' average annual rate of increase in electricity consumption was 3.5%, and from 1979 to 1987 the rate declined to 2.4% [11].

Table I Electricity Intensity by Region and Selected Countries, 1987

Region/Selected Country	Electricity intensity kWh/US Cent
Subsaharan Africa	42
- Rwanda	8
- Zimbabve	176
LAC	63
- Guatemala	29
- Colombia	111
Asia	63
- Nepal	21
- India	99
- China	169
EMENA[1]	75
- Algeria	21
- Jordan	73
Total LDC (75 countries)	56
North America[2]	57
Western Europe[2]	40
Japan[2]	39

Note: [1] Europe, Middle East and North Africa Categorization made by World Bank for administrative purposes
[2] GDP in US$ of 1985

Source: [3], [11], and own calculations

Simple regression analysis confirms the trend towards a higher electricity intensity in LDCs. Assuming that the elasticity of electricity consumption varies with the level of income, the electricity requirements of LDCs can be approximated by the equation:

$$Y = aX^{c} * e^{bx} \qquad (1)$$

where

e = exponent
Y = per capita consumption of electricity
X = GDP per capita
a,b,c = parameters to be estimated.

Based on cross-sectional data compiled for 75 developing countries [3], the following parameter estimates have been obtained (R^2 = 0.72, 95% confidence interval):

$a = 4.49 * 10^{-2}$
$b = -7.78 * 10^{-5}$
$c = 1.3547$

The results seem to comply with the widely held view that GDP growth, unless it is highly "random", serves as a reasonably reliable proxy for the driving forces that underlie the dynamics of aggregate electricity use. Moreover, since the (variable) elasticity of electricity consumption with respect to GDP is given by

$$E = (dY/dX) \;/\; (Y/X) = bX + c \qquad (2)$$

The findings suggest that, as GDP per capita rises from \$100 to \$4,560, the elasticity of electricity use declines from E = 1.35 to E = 1. Moreover since

$$d(Y/X) \;/\; dX = (Y/X^2) * (E-1) \qquad (3),$$

the electricity intensity increases (at a decreasing rate) until GDP per capita approaches the point (\$4,560) at which the elasticity of electricity consumption becomes equal to unity.

It goes without saying that the above estimates should not be mistaken as a basis for predicting future electricity demand in LDCs. The correlation between GDP-growth and changes in electricity consumption tends to be rather weak in low-income countries. And even in comparatively wealthy LDCs with a large power sector, the actual relationship between GDP and electricity use may, due to structural shifts, volatile GDP-growth, etc., change in an "erratic" way. (Note that time-series do not necessarily yield qualitatively better parameter estimates). What our estimates indicate, however, is that GDP growth will inevitably put a strong upward pressure on the intensity at which electricity is used in LDCs.

Also, potential improvements in end-use efficiency cannot be expected to halt the trend towards significantly higher electricity intensities. For instance, comparatively large electricity savings potentials are deemed to exist for end-uses such as lighting and refrigeration. Here, typical estimates range from 10% to 30% [9]. However, even if a 20% savings from overall efficiency improvements could be achieved over the next ten (twenty) years, this would cut the rate of increase in electricity use by only -2.2% (-1.1%) a year.

Thus, in the 1990s, the LDC's electricity consumption most probably will continue to grow faster than GDP, contrary to what can be expected in OECD countries where increases in electricity demand are likely to remain in close vicinity of the rate of economic growth. Planned capacity expansions in LDCs reflect the belief that electricity supply will rise at an average annual rate of 6.6% between 1989 and 1999 (see Section 3). But even though this figure is lower than the rates at which supply used to grow during the last two decades, it may still be considered overly optimistic given the internal and external constraints faced by the LDC's power sector.

2. UTILITY PERFORMANCE IN LDCs

The major internal constraint is poor sector management and performance. Clearly, measuring performance is a thorny issue, but a great deal of evidence unequivocally signals that over the last two decades things have turned for the worse.

As is recorded by key indicators shown in Table II, since the first oil price shock the financial health of electric utilities in LDCs has deteriorated steadily. The losses resulting from inadequate tariffs have probably been a factor that merits most of the blame for the increasing (internal) financial strains faced by the utilities. Between 1984 and 1988, tariffs (in constant US$) on average declined at a rate of 7.2% per annum and in 1988 dropped below the level that prevailed in 1979. Based on a sample of 26 countries, in 1988 the mean percentage deviation of tariffs from economic costs was -11.2% at the system level, and the bias towards under-recovery of costs generally increased from high to low voltage levels.

Table II Financial Indicators of Electric Utility Performance in LDCs (Annual Averages)

Indicator	1966/73	1974/79	1980/85	1986/87
Rate of return on assets (%)	9.2	7.9	6.0	4.4
Operating Ratio[1]	0.68	0.77	0.80	0.81
Self-financing ratio (%)[2]	24	17	18	19

Note: [1] Ratio of current expenses (including depreciation) to current revenues.
[2] Percentage share of investment requirements financed by internal cash generation.

Source: [6],[8]

Another factor that contributed to the financial losses experienced by many electric utilities was their inability to collect revenues in due time. The record of accounts receivables deteriorated from an average of 77 days (of revenues outstanding) in the period 1966-73 to 113 days in the first half of the 1980s [6], and most probably an increasing fraction of these claims have had to be written off. In addition, one can expect the share of unbilled electricity consumption to be large. Between 1980 and 1987, total losses (which, statistically, are equal to the difference between energy supplied to the system and energy sold) on average rose from about 20% to 23% of sales and in some cases were as high as 60% [8], compared to a figure of 12% which is considered "normal" for an efficiently managed system. Even though a detailed break-down of the recorded losses is not available, their exceptionally high level suggests that "non-technical" losses in the form of theft or unbilled consumption are pervasive.

As for truly technical losses, poor maintenance and failures in system design are the major areas of concern. Neglected transmission and distribution networks frequently proved responsible for power shortages and a low quality of supply even where the installed capacity was large enough to match demand. On the other hand, sub-optimal system configurations have impaired the utilities' ability to meet demand at least cost. In particular, facility planning was subject to increasingly large errors in forecasting demand. Table III shows that over the last twenty years the trend in projecting future electricity sales (on which system expansion programs were based) was biased by a steadily growing "appraisal optimism" (except for the early 1970s where the sudden rise in the oil price might have dampened the expectations about future growth). Actual sales increasingly lagged behind the estimated potential for power consumption, thus leading to a mismatch between installed supply capacities and effective demand. This put an upward pressure on unit generation costs which, though, was not reflected in the way tariffs have changed.

Table III Power Sales Forecasting Errors in LDCs[1]

Period		Year 3 Mean Annual Deviation (%)	Year 7 Mean Annual Deviation (%)
1960-65	Over	7 2	20.5
	Under	- 11.1	- 25.1
	Relative	1 7	4.5
1966-70	Over	14.1	16.7
	Under	- 5.8	- 8.5
	Relative	7.5	8.5
1971-75	Over	10.5	15.6
	Under	- 5.2	-16 3
	Relative	6 8	7.4
1976-80	Over	16 8	30 9
	Under	- 3.6	-
	Relative	12 8	30.9
1980-85	Over	18.4	
	Under	- 8 2	n a
	Relative	15 7	

Note [1] "Over" and "Under" figures express the differences between forecasted and actual sales as a percentage of actual sales The "relative" deviation is a measure of the forecasting bias

Source [7]

It seems that in the late 1980s the trend towards performance degradation come to a halt. At least, efforts are underway that are hoped to lay the groundwork for improvements in sector management and organization. But pending the success of these measures, many electric utilities in LDCs will remain to be saddled with inefficiencies and financial difficulties inherited from the past.

3. EXISTING AND PLANNED GENERATION CAPACITY

A recent study conducted by the World Bank [5] provides a fairly comprehensive picture of the existing and planned power generation capacities in LDCs. The data used by the study are compiled from (internal) World Bank documents on power sector expansion programs envisaged by electric utilities in 70 LDCs which account for more than 95% of the power sector facilities installed in developing countries. The list of countries includes Portugal, Hungary, Poland and Yugoslavia which are World Bank borrowers, but may not be considered as "typical"

LDCs. Also, Poland, Hungary and Yugoslavia are frequently lumped under the category of Eastern Europe, while Portugal figures as an ECE member. Therefore, we refer to narrowly defined LDCs whenever the data do not cover the four "atypical" LDCs.

In 1989, the LDCs' total installed generation capacity amounted to 471 GW which is roughly 18% of the capacity installed worldwide (Table IV). A distinguishing feature of the LDC's generation capacity are the comparatively large shares accounted for by hydro (39%) and coal (36%). Not surprisingly, nuclear generating capacity (3%) plays a significantly less important role than it does in North America (12.6%) or Western Europe (21.8%). The different status of nuclear power is even more striking at the level of electricity supply. While in LDCs nuclear energy accounts for only 4% of the total electricity output (Table V), the share of nuclear electricity generation is 19% in North America and 31% in Western Europe.

Also, existing reserve capacities are excessive due to planning failures, frequent breakdowns and lengthy outages. In about 75% of LDCs, the installed capacity exceeds system peak by more than 40%, and in 28% of the countries the margin is greater than 60% (compared to 25% in systems considered efficient).

Table IV Generation Capacity in LDCs[1]

	Estimates 1989		Planned 1999		Increase	
	GW	% share	GW	% share	GW	%share of increase
Hydro	185 (171)	39.3	322 (303)	37.7	137 (132)	35.7 (36.8)
Geothermal	2 (2)	0.4	5 (5)	0.6	3 (3)	0.8 (0.8)
Nuclear	14 (12)	3.0	38 (30)	4.4	24 (18)	6.2 (5.0)
Oil thermal[2]	70 (64)	14.8	84 (79)	9.7	14 (15)	3.5 (4.2)
Gas thermal[3]	31 (29)	6.7	65 (60)	7.8	34 (31)	9.3 (8.6)
Coal thermal	169 (129)	35.8	341 (289)	39.8	172 (160)	44.5 (44.6)
TOTAL	471 (407)	100.0	855 (766)	100.0	384 (359)	100.0 (100.0)

Note: [1] Figures in paranthesis do not include Portugal, Poland, Hungary and Yugoslavia
[2] Includes steam, combustion turbine, combined cycle and diesel
[3] Includes steam, combustion turbine and combined cycle

Source: [5]

Capacity expansion plans call for additional 384 GW to be installed during the 1990s, increasing the LDC's generation capacity by 82% to 855 GW at the turn of the century (Table IV). Salient points of these planned additions are:

- Coal will be the major source of power, increasing its share in total generation capacity (output) to almost 40% (47%).

- While gas will improve its position vis a vis oil, the share in total generation capacity (output) accounted for by hydrocarbons will decline (in spite of the partly aggressive plans to utilize domestic gas resources).

- Hydro will maintain a capacity share of roughly 38%.
- Nuclear continues to be a small component, and there is considerable uncertainty concerning nuclear additions beyond the 1990s.

Table V Electricity Supply in LDCs[1]

	Estimates 1989 TWh	% share	Planned 1999 TWh	% share	Increase TWh
Hydro	674 (630)	33.2	1,207 (1,154)	31.5	533 (524)
Geothermal	11 (11)	0.6	29 (29)	0.8	18 (18)
Nuclear	80 (65)	3.9	212 (152)	5.5	132 (87)
Oil thermal	224 (215)	11.0	255 (252)	6.6	31 (37)
Gas thermal	120 (111)	5.9	332 (310)	8.6	212 (199)
Coal thermal	907 (698)	44.7	1,793 (1,518)	46.6	886 (820)
Net Imports	14 (3)	0.7	16 (5)	0.4	3 (2)
TOTAL	2,030 (1,733)	100.0	3,844 (3,420)	100.0	1,815 (1,687)

Note: [1] Figures in paranthesis do not include Portugal, Poland, Hungary and Yugoslavia

Source: [5]

In the narrowly defined LDCs the picture is essentially the same. Total capacity is planned to increase by 88% (359 GW). There will be a shift towards coal at the expense of the relative share of oil thermal capacity. The use of gas will double, but this does not entail a significant increase in the share of gas thermal capacity. Hydro is expected to keep a capacity share of 40%, while the share of nuclear generating capacity will not exceed the 4% level.

Almost two thirds of the new capacity will be installed in Asia where 81% of the coal thermal additions and 57% of the hydro additions are planned to take place. About 18% of the new capacity will be added in the EMENA region which accounts for 53% of the overall increase in gas thermal capacity. LAC's share in total capacity additions is 17% of which two thirds are provided for by hydro. Africa, on the other hand, will only marginally contribute to the developing countries' capacity additions (Table VI).

If the EMENA-countries Portugal, Hungary, Poland and Yugoslavia are excluded, the regional mix of capacity additions shows an even stronger bias towards Asia. More than two-thirds of the narrowly defined LDCs' additional generating facilities will be installed in Asia; LAC accounts for 18.4% of the new capacity, and Africa remains a negligible component.

China and India alone account for two thirds of the coal thermal additions. Nonetheless, in a large number of other countries the planned increase in coal use will be significant in both absolute and relative terms. For instance, countries like Korea, Thailand, Indonesia or Turkey have earmarked coal thermal additions that exceed the total capacity

Table VI Regional Breakdown of Planned Capacity Additions in LDCs (in GW)[1]

	Asia	EMENA	LAC	Africa	Total
Hydro	78	15 (10)	42	2	137 (132)
Geothermal	2	- (-)	1	-	3 (3)
Nuclear	14	7 (1)	3	-	24 (18)
Oil thermal	- 3	4 (5)	12	1	14 (15)
Gas thermal	13	18 (15)	2	1	34 (31)
Coal thermal	140	25 (13)	6	1	172 (160)
TOTAL (GW)	244	69 (44)	66	5	384 (359)
(%)	63.5 (68.0)	18.0 (12.3)	17.2 (18.4)	1.3 (1.4)	100.0 (100.0)

Note: [1] Figures in parenthesis do not include Portugal, Poland, Hungary, and Yugoslavia

Source: [5]

Table VII Coal Thermal Generation Capacity by Country

	Estimates 1989		Planned 1999		Increase	
	GW	% of total	GW	% of total	GW	%share of increase
China	72.4	42.9	136.7	40.2	64.3	37.4
India	38.0	22.5	90.4	26.6	52.4	30.5
Korea	3.7	2.2	12.5	3.7	8.8	5.1
Indonesia	1.7	1.0	9.7	2.9	8.0	4.7
Thailand	1.2	0.7	5.4	1.6	4.2	2.4
Pakistan	0.01	-	3.7	1.1	3.7	0.6
Mexico	1.2	0.7	4.0	1.2	2.8	1.6
Brazil	1.0	0.6	2.8	0.8	1.8	1.1
Colombia	0.7	0.4	1.3	0.4	0.6	-
Zimbabve	1.4	0.8	1.8	0.5	0.4	7.2
Poland	27.8	16.5	33.1	9.7	5.3	3.1
Turkey	3.9	2.3	9.5	2.8	5.6	3.3
Yugoslavia	10.2	6.0	15.3	4.5	5.1	3.0
Others	5.5	3.2	14.1	4.0	8.6	-
TOTAL	168.8	100.0	340.3	100.0	171.5	100.0

Source: [5]

increase planned for Africa. Also, the planned increase in coal thermal capacity net of additions called for in India and China exceeds the sum of the LDCs additions in oil and gas thermal capacity.

Notwithstanding the fact that coal tends to fall out of fashion in the developed world and contrary to the hopes energy planners pin on the role to be played by "cleaner" fuels, the LDC's power sector will increase its relative reliance on coal rather than gas (or nuclear generation).

4. ENVIRONMENTAL IMPLICATIONS

Given the planned capacity additions, there are two potential areas of environmental concern: The development of hydro power schemes may have adverse impacts on flora/fauna, water quality, etc. and may cause social and economic disruptions. And the expansion of oil, gas, and coal thermal capacity will increase atmospheric pollution. As regards the latter problem, the major challenge will be posed by coal. As is shown in Table VIII, more than three quarters of the primary fossil fuel requirements that result from the planned capacity expansion programs in narrowly defined LDCs will be met with coal, the "dirty" fuel par excellence. Among the gaseous emissions (CO_2, CO, SO_2, etc.) and particulates that the increased use of coal in power generation can be expected to release, carbon dioxide is considered to be the most critical variable (if only because there are no technically proven and economically justified options for removing CO_2 above and beyond the level set by the dissolution in the ocean and the uptake by biomass). Moreover, it is widely agreed that for the prospect of CO_2-concentrations to raise well above the alleged critical threshold of 600 ppm, the amount of coal combusted worldwide will be a crucial factor. So it may be useful to put the CO_2 emissions released by power generation in narrowly defined LDCs into a global perspective.

Table VIII LDC Fossil Fuel Requirements for Electricity Generation[1]

	1989	1999	Increase	% share of Increase
Oil[2] (million tons)	54	63	9	3.4
Gas[3] (TCF)	1.1	3.1	2	18.9
Coal[4] (million tons)	349	759	410	77.7
TOTAL (million toe)	256	520	254	100

Note: [1] not including Portugal, Poland, Hungary and Yugoslavia
[2] 0.25 kg/kWh
[3] 10 CF/kWh
[4] 0.50 kg/kWh

Source: Table V

Currently, global energy-related CO_2 emission are estimated at 6 Gt C/year, of which about 1.3 GtC are accounted for by electricity generation. According to rough calculations (see Table IX), power generation in (narrowly defined) LDCs contributed 225 Mt C in 1989 which is equivalent to 17% of the global power-dependent CO_2 emissions (or about 4% of the global energy-related emissions). In other words, by global standards, LDCs power generation currently is a marginal contributor of carbon dioxide emissions.

However, while the Toronto Conference called for a 20% reduction in global CO_2 emissions which would bring down the emission rate to 4.8 GtC/year by 2005, the LDCs' power sector will be of little help in accomplishing this task. On the contrary, if - as it is planned - the LDCs generating capacity increases by 88% over the next decade, this will more than double the sector's CO_2 emissions, i.e. at the turn of the century power generation in LDCs would release 455 Mt C/year (see Table IX). So if the rest of the world were to succeed in reducing the power related CO_2 emission by 20% (which is equivalent to 220 Mt C/year), this effort would just be offset by the extra CO_2 that the LDCs' power sector is planned to emit.

Table IX LDC Power Sector Contribution to CO_2 Emissions[1] (in million tons of Carbon)

	1989	1999	Increase
Oil[2]	41.58	48 51	6 93
Gas[3]	15 07	42 47	27 40
Coal[4]	167 52	364 32	196 80
TOTAL	224 17	455 30	231 13

Note. 1 excluding Portugal, Hungary, Poland and Yugoslavia
2 0 77 kg C per kg of oil
3 13 70 kg C per BCF of gas Figures do not account for the Debatable role played by the higher absorptivity of methane
4 0 48 kg C per kg of coal

Source Table VIII

Table X Increase in Power-Related CO_2 Emission in Selected LDCs[1]

	— million tons of carbon —				% share in total	Carbon Intensity[2]
	Oil	Gas	Coal	Total		
China	-	-	94.13	94 13	40 7	176 79
India	0 05	0 71	41 42	42 13	18 2	122 36
Mexico	8 49	2 74	3 84	15 07	6 5	154 70
Korea	0 45	0 73	12.05	13 23	5 7	175 31
Indonesia	(0 58)	1 68	11 57	12 67	5 5	201 36
Thailand	0 01	1 33	6 82	8 16	3 5	203 08
Turkey	(0 82)	1 14	7 82	8 19	3 5	145 56
Egypt	(0 63)	3 98	2 83	6 18	2 7	185 35
Pakistan	(2 19)	0 92	4 65	3 38	1 5	76 15
Brazil	1 19	-	3 06	4 25	1 8	29 43
LDC Total	6 93	27 40	196 13	231 13	100 0	127 39

Note [1] Difference between emissions in 1999 (planned) and 1989 (actual) Negative figures in parenthesis
[2] tons of carbon per additional GWh generated by the electricity sector

Table X provides information on the increase in CO_2 emissions associated with the planned capacity additions in selected LDCs. Almost 60% of the total increase is accounted for by China and India. However, the carbon intensity of incremental electricity generation will be highest in Indonesia and Thailand where the share of hydropower is comparatively small. By the same token, the carbon intensity proves lowest in Brazil where almost 80% of the additional electricity is expected to come from hydropower resources.

All in all, there is little leeway for a shift away from coal. The use of gas is already aggressively pursued (as is reflected in the capacity expansion plans), but this will help little more than to catch up with the decline in the share of oil thermal capacity. Nuclear power fails to be a strategic alternative; and hydropower resources which are abundant in many LDCs are difficult to develop more rapidly than is currently the case.

While the trend towards coal may be considered harmful from the angle of atmospheric pollution, the concerns about the development of hydropower resources focus on socio-economic impacts (e.g. resettlement) and the potential damage for (local) ecosystems. In the past, heavy environmental criticism has centered on hydropower schemes that involve "large" dams. (A dam is considered "large" if it meets at least one of the following criteria: dam height of at least 150 meters; dam volume of at least 15 million cubic meters; reservoir capacity of at least 25 cubic kilometers; installed hydropower capacity of at least 1 GW). Currently, there are some 69 large dams associated with about 65% of the hydropower capacities installed in LDCs. And large dams will continue to be a critical component in the development of hydropower resources [1].

As is shown in Table XI, hydropower expansion in LDCs slowed down in the 1970s, but capacity growth resumed in the 1980s and is planned to continue at an average annual rate of 5.7% until the end of the century. Given the fact that in 1989 more than 90% of the total technically usable hydropotential in LDCs was untapped, it can be expected that the development of additional resources will remain a strategic option well beyond the year 2000. In the industrialized world, by contrast, the scope for hydroelectric expansion is much more limited is indicated by the declining trend in capacity growth.

Table XI Historic Trends in the Growth of Hydropower Capacity[1]

	1950-60	1960-70	1970-80	1980-89[2]	1989-99
LDCs[3]	8 0	10 1	4 9	6 0	5 7
Industrialized Countries[4]	12 1	6 1	4 8	2 5	n a

Note [1] Average annual % rate of capacity growth Planned growth for the period 1989-99
[2] 1980-86 for industrialized countries
[3] Capacity installed 1989 185 GW
[4] Capacity installed 1986 413 GW

Source [2], [5]

China, India and Brazil account for about 42% of the LDCs' total hydro potential. Moreover, power demand is not likely to be a major constraint to the development of the hydro resources in these countries. So it does not come much as a surprise that about 75% of the planned increase in hydroelectric capacity is in India, China, and Brazil. Other countries that are endowed with sizeable hydro resources and face a sufficiently large power market justifying their development include Argentina, Pakistan, Turkey, Mexico, and Columbia. In all cases scenarios which significantly reduce the role of hydropower without constraining power supply are hard to conceive. In order to meet additional demand there will be massive requirements for an increased use of hydropower. Sunshine, wind, or energy conservation do not provide alternatives suited to relieve the need for a large-scale expansion of hydroelectric capacity. Nor are there sufficient (and cheap) gas, oil or coal reserves that could substitute for the role hydropower is expected to play

As a consequence, since there is little choice but to continue developing large-scale hydropower schemes, a number of countries will have to cope with the environmental problems that these projects may pose. Fortunately, the envisaged pace of hydropower expansion looks modest so that careful planning, with due consideration given to environmental issues, should be feasible. However, it cannot be ruled out that ecological concerns and, thus, a re-evaluation of costs and benefits will slow down the rate at which the hydropower capacity is expected to increase in some LDCs.

In sum, it can be stated that there is no reason to be overly worry about the environmental implications that the programs for power sector expansion in LDCs are likely to have during the 1990s. There will inevitably be atmospheric pollution. In particular, if the sector grows at an average annual rate of 6.5% (which is the optimistic view underlying the expansion plans), the level of power-related CO_2 emissions will double at the turn of the century. Yet this increase could easily be offset by a 20% reduction in CO_2 emissions attributable to power generation in industrialized countries.

Also, countries like China or India have no choice but to match a significant part of the planned increases in generation capacity through the development of comparatively abundant hydropower resources. While large hydroelectric schemes may have adverse environmental and socio-economic consequences, the problems, in principle, appear to be manageable.

5. FINANCIAL CONSTRAINTS TO POWER SECTOR EXPANSION

The above data on the LDC's power sector expansion plans should not be mistaken as a World Bank demand forecast. Nor should they be considered a supply-side scenario that the World Bank expects to materialize during the 1990s. Rather, the figures reflect the ambitious system expansion programs developed, committed or proposed by LDCs electric utilities, in most cases with the approval of governments. Put in this perspective, the data may contain a large element of wishful thinking.

In fact, a major obstacle to the LDC's sector expansion plans will be the limited availability of financial resources needed to maintain and reinforce existing facilities (an area of neglect) and to invest in new capacity. In the past, power sector investment in LDCs had been financed mainly through medium to long-term loans from foreign commercial banks, export credit agencies and concessional sources. However, in the early 1980s buoyant foreign lending for LDCs power development came to a halt. Lending peaked in 1981 (about US$ 14.3 billion), but then dropped to US$ 7.1 billion in 1983, and remained at this level in the years thereafter. The 50% decline in foreign exchange available for power investments was accompanied by a dramatic reversal in the relative shares of foreign exchange from private and official sources: While official creditors increased their share in total power sector lending from 30% in 1981 to 81% in 1987, the private creditors share declined from 70% to 20%. Since lending from official sources kept roughly at the level that had prevailed in 1981 (US$ 4 billion), the worsening of the financial situation can entirely be attributed to the drain of commercial loans.

As there is little prospect of any change for the better during the 1990s, the LDC's power sector expansion plans are doomed to experience a severe shortfall of financial resources. Total investment requirements between 1989 and 1999 are likely to amount to US$ 745 billion (in prices of 1989) of which the foreign exchange component is US$ 285 (see Table VIII). With allowances for price escalation and cost overruns, the total (local funds plus foreign exchange) may well be in the order of US$ 1 trillion.

On the other hand, if foreign lending continues to remain at current levels (US$ 7-8 billion per year), the available foreign exchange might be in the range between US$ 70 and US$ 80 billion, which would be just enough to service the existing foreign debt for past power developments over the next four to five years (not including the recurrent cost of imported fuel and spare parts). So even if the LDCs were to succeed in rescheduling their existing debt, the additional foreign exchange requirements to be met during the first half of the 1990s would still amount to US$ 145 billion (or US$ 29 billion per year). And unless the LDCs' power sector succeeds in significantly improving the prospects for good performance, the foreign exchange gap is likely to widen beyond the mid-1990s.

It goes without saying that, due to the sector's poor shape, the financing requirements for the local cost components of the capacity expansion plans appear to be as forbidding as are the financing needs in terms of foreign exchange.

Table XII LDC Capital Expenditures for Power Sector Development, 1989-1999 (in US$ billions of 1989)

	Asia	EMENA	LAC	Africa	Total	%
Generation	277	82	83	6	448	60.0
Transmission	39	8	32	2	81	10.9
Distribution	100	23	27	2	152	20.5
General	39	11	13	1	64	8.6
TOTAL	455	124	155	11	745	100.0
% of Total	61.1	16.6	20.8	1.5	100.0	
of which:						
foreign exchange	158.0	72.6	46.0	7.9	285.0	38.0
local currency	297.0	51.4	109.0	3.1	460.0	62.0

Source: [5] and IENED

6. CONCLUSIONS

Given the fact that power demand in LDCs is highly income elastic, demand will be driven by GDP growth and constrained by supply. Supply-based scenarios of future consumption of electricity, however, have to come to terms with apparent lack of financial resources that tend to hamper planned investments in additional capacity.

Whether or not the shortfall of finance for power sector development in LDCs can be overcome, sector expansion, both in terms of electricity generation and capacity additions, will heavily rely on coal thermal solutions. Also, hydropower will continue to play an important role. Taken together, coal thermal and hydropower facilities are likely to account for 80% of the incremental electricity supply scheduled for the 1990s. This may prompt different environmental problems. In the case of coal, the additional emissions will contribute to a doubling of the annual amount of CO_2 released by the LDCs' power sector. However, put in a global perspective, the scenario is not yet alarming.

On the other hand, while environmental considerations do not pose an unsurmountable obstacle to the continued, large-scale development of hydropower resources, they may call for a more careful appraisal of the available options, lead to higher (internalized) costs or cause a delay of some of the hydropower expansion projects.

Indeed, given the financially fragile position of many LDCs utilities and taking into account the severe difficulties in raising the funds required to implement the scheduled capacity additions, it can be expected that power sector growth in LDCs will prove to be much slower than is envisaged by the expansion plans. This view is also supported by the fact that in the near future considerably more emphasis must be placed on revamping sector organization and management. Therefore, the 6.5% rate of growth which is implied in the sequence of investments planned for the 1990s should be adjusted downwards. A more reasonable guess would be an average annual increase between 4% and 5%, a range which is roughly in line with projections underlying modest growth scenarios a la "Energy for a Sustainable World" [4].[1] Consequently, a more realistic time horizon would be that the sector expansion program scheduled for the 1990s will be completed not before 2005.

The most obvious candidates for conservation measures are excessive reserve margins and system losses. Here, improvements are a matter of system design, maintenance and operational efficiency. The overall scope for additional savings from improvements in electricity end-use efficiency that are technically feasible and economically viable may prove large in many LDCs; but much more effort needs to be taken in order to identify, probe and access this savings potential both in the short and in the long-run.

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THE OUTLOOK FOR ELECTRICITY EFFICIENCY IMPROVEMENTS IN DEVELOPING COUNTRIES

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ABSTRACT: Energy efficiency improvement is a promising way to reconcile needs for economic and social development with reducing pressures on the global environment, as well as pressures on capital supply systems for development. Requirements for increased electricity services are growing too rapidly for conventional supply-side strategies to remain feasible for many countries, while evidence of the potentials for efficiency improvement is emerging nearly as rapidly. The problem is that technological feasibility alone does not assure efficiency improvement; a number of stubborn policy, institutional, and behavioral obstacles must be overcome. As result, how much efficiency improvement will be accomplished in most developing countries will depend heavily on the efficacy of public policies, both in developing countries and in the international community, and on the effectiveness with which policy initiatives are pursued.

1. INTRODUCTION

Improving the efficiency of the systems which deliver the benefits of electricity to the citizens of developing countries is an appealing way to reconcile needs for economic and social development with reducing pressures on the global environment. This paper summarizes the outlook for such efficiency improvements under a variety of policy conditions, together with the issues that are central to any discussion of the outlook, suggesting that:

(a) What people want from electric power systems are electricity services, not kilowatt-hours.

(b) Efficiencies in electric power generation, distribution, and use make it possible to provide more services per unit of energy consumed (and waste substances emitted) at the point of electricity generation.

(c) In this sense, efficiency improvement is a 'supply' alternative: in other words, it is an alternative to additional power generation as a way to supply more electricity services.

(d) From a development perspective, efficiency improvement should be the preferred investment whenever its net social benefits are greater than more conventional supply-side additions.

The fundamental questions are how often this will be the case, given the enormous diversity of developing country situations, and how likely it is that prospects which appear attractive on the basis of distant analysis will be realized under local institutional conditions.

2. THE OUTLOOK FOR ELECTRICITY SERVICE REQUIREMENTS OF DEVELOPING COUNTRIES

Clearly, developing countries need more electricity services than they receive at present. Electricity services mean such economic and social benefits as comfort, convenience, and labor productivity – contributing both to the development process itself and to an enjoyment of the fruits of the process. But meeting these needs over the next several decades is likely to test the limits of world's economic and environmental systems.

2.1 General relationships

It is quite clear that energy services are closely related to the quality of life. Historically, available data suggest that economic growth in a developing country of 1% per capita has been associated with an increase in the primary consumption of 'modern' fuel sources (i.e., electricity and liquid/gas fossil fuels) of 1.3 to 2% per capita [1]. Taking a multiplier of 1.3 as a conservative approximation, Fig. 1 indicates how human appetites for energy services combine with economic and population growth to create growing demands on energy systems in developing countries.

We have, however, learned that these curves represent demands for energy services, such as convenience and mobility, not necessarily demands for energy products themselves such as kilowatts of electricity or liters of diesel fuel. In some situations, efficiency improvements can make it possible to decouple energy service growth from energy supply growth, although consumers (especially at lower levels of well-being) may choose to invest some of the resulting benefits in additional energy services rather than reduced energy consumption.

In any event, current energy consumption in developing countries is typically about one-quarter of the global average (Fig. 2). Narrowing the North-South economic gap will require narrowing this energy service gap, which means a substantial increase in the energy services provided to low- and middle-income countries in Asia, Africa, Latin America, the Middle East, and Eastern Europe.

2.2 Projections of requirements

Most people are convinced, in fact, that the developing countries will account for a very large part of the aggregate increase in global energy consumption during the next century. Table I, for example, summarizes projections prepared for the 1989 World Energy Conference by the World Energy Council, using a network of thirty regional experts [2]. These forecasts suggest that about 60% of the increases to be expected in a 'moderate growth' case will come from developing countries, with about another 20% from Eastern Europe.

Other recent forecasts present a similar picture. For instance, in 1988 the USA Agency for International Development (A.I.D.) considered the possibility that an electric power crisis is emerging in many developing countries, related to a combination of rising demands and stubborn capital supply constraints [3]. A.I.D. projected electricity consumption (in the 'business as usual case') as 1.4 times the forecasted rate of economic growth, using World Bank estimates of economic growth rates: 3.4%, 4.5%, and 5.5% in low, medium, and high economic growth scenarios, respectively. The result was an estimated growth in electricity generation capacity in developing countries from 450 GW in 1989 to 1950 GW in 2008 in the moderate growth case.

Table I Shares of World Energy Consumption

	1985[1]	2020[2]	Increase
Western industrialized countries	47%	36%	21%
Eastern Europe	23%	21%	20%
Third world	30%	43%	59%
TOTAL (in Mtoe)	7670	13525	5855

Note: [1] Actual
[2] Projected (World Energy Council - 'moderate scenario' [5])

A very recent survey by the World Bank supports this kind of vision of the future. According to data from 70 developing countries, those countries plan to add 384 MW of electricity generation capacity during the decade of the 1990s, half based on coal (mainly in China and India) and much of the rest on large-scale hydroelectric facilities [4].

To date, the most comprehensive effort in the United States of America to analyze developing country energy trends has been in connection with a study by the USA

Environmental Protection Agency (EPA) of 'policy options for stabilizing the global climate' [5]. Still available only as a draft report, this study describes two scenarios bounding the range of likely futures – a 'rapidly changing world' (RCW) and a 'slowly changing world' (SCW) – plus 'policy cases' for each, estimating possible reductions in CO_2 emissions through policy initiatives. Forecasts are disaggregated by nine major regions of the world, with the developing country portion prepared by the Lawrence Berkeley Laboratory (LBL), utilizing experts familiar with regional conditions [6]. Table II and Figs. 3-5 summarize the approach and the results.

Table II Overview of EPA Scenario Assumptions [5]

Slowly changing world
Slow GNP growth Continued rapid population growth Minimal energy price increases Slow technological change Carbon-intensive fuel mix Increasing deforestation Montreal protocol/low participation
Rapidly changing world
Rapid GNP growth Moderated population growth Modest energy price increases Rapid technological improvements Very carbon-intensive fuel mix Moderate deforestation Montreal protocol/high participation
Slowly changing world with stabilizing policies
Slow GNP growth Continued rapid population growth Minimal energy price increases/taxes Rapid efficiency improvements Moderate solar/biomass penetration Rapid reforestation CFC phase-out
Rapidly changing world with stabilizing policies
Rapid GNP growth Moderated population growth Modest energy price increases/taxes Very rapid efficiency improvements Rapid solar/biomass penetration Rapid reforestation CFC phase-out

Since neither of these scenarios is intended as a 'best guess' about the future, A.I.D. recently asked LBL and others to create a more realistic mid-range scenario, as part of the development of a broadly-based 'Global Energy Efficiency Initiative' (GEEI). The most fundamental stepping-stone in describing a realistic scenario, of course, is determining the assumptions to be adopted about such basic parameters as economic growth rates (i.e., annual growth in Gross Domestic Product, or GDP) and population growth rates. For a May 8, 1990 draft report [7], economic growth rates were based on projections developed for the USA Department of Energy (DOE). Figures 6 and 7 and Table III indicate the resulting estimates of energy use: for developing countries and Eastern Europe, growing by a factor of about three between 1985 and 2025.

The problem in this case is that, in the 'Reference Scenario,' the assumed rate of economic growth meant serious resource constraints in several regions unless energy efficiency was improved substantially (Tables IV and V). For example, unless energy efficiencies improved by 50% in China, the assumed rate of growth in GDP could not be realized because capital requirements (and others) were unattainable. This means, in effect, that in this scenario the outlook for efficiency improvement is driven by modeling assumptions rather than realistic institutional evaluations – and that the efficiency assumptions are in a number of cases probably too optimistic, unless effective policy interventions occur. A revised Reference Scenario, based on perhaps more realistic assumptions about economic growth rates, is currently being discussed.

Regardless of the details, we have known for more than a decade and a half that this situation presents the world with a challenge of bringing about an energy transition in the next century that is truly one of the greatest scientific and institutional challenges of our time: a shift away from liquid and gas fossil fuels at the same time that we meet rapidly rising demands of developing countries for energy services. Georgescu-Roegen has called this a 'Promethean' challenge, analogous to the shift from wood to coal associated with the industrial revolution [8]. Meanwhile, we do not know yet what we are shifting to, when none of the currently available alternatives are very attractive. What we do know is that, in bringing about this transition, it is likely that every limit we know will be tested: limits in the acceptable costs of energy, in acceptable environmental impacts from producing and using energy, in the capabilities of our research and development institutions, in the performance of our institutions, in participatory ways of making decisions. There will be strains. There will be scapegoats. And the longer we wait to develop better options, the greater the strains will be [9].

Table III Growth of Primary Energy Use Between 1985 and 2025 (percent per year)

	Reference Scenario	Efficiency Scenario	GDP Growth
Latin America	2.4	1.8	2.9
S&E Asia	3.9	3.2	5.0
China	3.1	2.7	4.9
Africa	2.8	2.1	2.6
Middle East	4.1	3.6	4.3
Eastern Europe	1.5	0.2	3.2
LDCs & Eastern Europe	2.9	2.3	3.8

Source: [7]

Table IV Change in the Ratio of Primary Energy Consumption to GDP (percent change relative to 1985)

	Reference Scenario	Efficiency Scenario
Latin America	- 18	- 36
S&E Asia	- 33	- 50
China	- 50	- 57
Africa	+ 8	- 18
Middle East	- 5	- 22
Eastern Europe	- 47	- 68
LDCs & Eastern Europe	- 32	- 47

Source: [7]

Table V Index of Energy Efficiency in Industry, 1985 = 100

	1985	2025 Reference	2025 Efficiency
Fuel Intensity[1]			
Latin America	100	68	45
Asia	100	70	56
China	100	45	38
Africa	100	87	70
Middle East	100	80	70
Electricity Intensity[2]			
Latin America	100	95	70
Asia	100	76	53
China	100	69	61
Africa	100	100	85
Middle East	100	110	95

Note: [1] TOE/10E6 1985$ indus. value-added
[2] MWh/10E6 1985$ indus. value-added

Source: [7]

The new part of the equation for the 1990s is the rising concern about global environmental change, related directly to fossil fuel use and deforestation [10]. With fossil fuel use accounting for an estimated 57% of global carbon emissions – the main causative agent in anthropogenic climate change – and developing countries and Eastern Europe expected to account for most of the growth in global fossil fuel emissions over the next several generations (see Section 3.1.2), the worldwide dialogue about responses to such issues as global warming is likely to focus especially on fossil energy use in developing countries. In addition, large-scale hydroelectric power development, the main alternative in many developing countries for relatively large-scale electric power production, also faces serious questions about environmental impacts [11]. This is not a new concern, but the increasing sense of urgency about the issue suggests increasing constraints on the energy resource/technology choices of developing countries, at the very time that their needs for energy services are rising and their financial resources for energy-sector investments are already pinched.

2.3 Impacts of failing to meet needs for electricity services

The problem is that, in a very fundamental sense, a failure to meet the needs of the Third World for an increase in electricity services by a factor of, say, six to ten over the next several decades means that the engine of development will slow. The relationship between electricity services and development is, in fact, neither direct nor simple. For example, if an electric utility in a developing country is unable to meet a power supply need, the end user can generate the electric power itself or, in some cases, meet needs for shaftpower or other energy services through mechanical or thermal energy rather than electricity. The overall costs may be higher, compared with a country with an efficient electric power infrastructure, and the barriers to market entry for new entrepreneurs may be correspondingly higher, but development can still take place in different ways.

Even so, a lack of available electricity services can discourage new productive activities, and unreliable electricity supplies can result in costs related to equipment damage and product spoilage [3]. Assessments of such impacts are scarce; but a 1985 study by the Indian National Council of Applied Economic Research (NCAER) estimated that production losses in that country due to power shortages amounted to about US $2.7 billion in 1983-84 (in 1987 dollars), or about 1.5% of GDP [12], and a 1987 study for Pakistan estimated the cost of power interruption and load shedding in the industrial sector at about 8% of value added [13]. Table VI summarizes the results of the studies available as of early 1988.

More profoundly important in many countries, however, is the fact that electricity services are closely related to improvements in the quality of life, such as comfort and convenience. As incomes rise as a result of successes with the development process, citizens expect to reap the benefits of their efforts. If their public-sector institutions do not meet these expectations, the result can be social and political instability. One recent example has been the Philippines, where daily electricity blackouts in April 1990 led directly to political discontent [14].

3. INCENTIVES FOR ELECTRICITY EFFICIENCY IMPROVEMENTS

Given this challenge and the time periods required for developing better energy supply technology alternatives, the most immediate effect of the current situation is to encourage attention to efficiency improvements, as the leading edge of a growing willingness by both developing countries and development assistance agencies to consider new approaches to meeting energy service needs.

3.1 Pressures to find alternatives to supply-side additions

Because of the pressures described above, it appears that a new era is at hand in electric power system planning in most developing countries. Social and political imperatives to expand electricity services, combined with virtually insurmountable obstacles to meeting such a need in conventional ways, are opening doors for innovations ranging from efficiency improvement to private sector roles in power generation. The two most important of the hurdles are capital scarcity and international concerns about global environmental change.

Table VI Costs of Power Shortages in Selected Developing Countries (1978 US$)

Country	Sector(s)	Type of Shortfall	Cost of Shortage
Bangladesh	All	Unplanned outages	1.00$/kWh
Brazil	Households	Unplanned outages	1.95-3.00$/kWh
Chile	Households	Unplanned outages	0.53$/kWh
	Industry	Unplanned outages	Range: 0.25-12.00$/kWh Central Tendency 1.50-6.00$/kWh
Costa Rica	Households	Unplanned outages	-
Egypt	Industry	Unplanned	0.40$/kWh
India	Industry	Controlled load shedding	Annual cost ranges from 1 to 3% of GDP (1.5 to 3 billion dollars annually)
Jamaica	Industry	Unplanned outages	1.25$/kWh
Pakistan	Industry	Controlled load shedding	Range: 0.26-1.77 Average: 0.46$/kWh
		Unplanned outages	Range: 0.36-2.54 Average: 0.81$/kWh
		Controlled and Uncontrolled load shedding	$350 million in 1984-85
Paraguay	Residential		-
Taiwan	Industry		0.06-2.16$/kWh
Tanzania	Households		0.50$/kWh
	Industry		0.70-1.40$/kWh
	Commercial		1.00$/kWh
	All sectors		0.70-1.10$/kWh

Source: Oak Ridge National Laboratory [15].

3.1.1 Capital requirements for additional electric power generation

For the developing countries themselves, the main concern is that the investment capital required for additional electric power generation will be unavailable, because of the sheer magnitude of the requirements and limited investor confidence in the ability to repay (due to total current levels of national indebtedness and questions about the performance of electricity supply institutions). For example, the World Bank survey of seventy developing countries indicated that generating capacity additions planned for the 1990s will call for US $750 billion in capital investment. The annual average level of US $75 billion is about 50% above the current total rate of power sector investment in developing countries, and the ten-year total approaches the total current level of indebtedness of the countries involved (about US $1 trillion) [4]. The preliminary GEEI analysis, based on less ambitious assumptions about growth rates, still showed investment requirements for the electric power sector in developing countries and Eastern Europe in the US $100 billion per year range in the 2001-2025 period [7]. The A.I.D. power crisis study estimated an average cost of more than US $125 billion per year through the first decade of the next century (in the moderate growth case). Raising such quantities of capital, while other development needs and other world regions compete for available supplies, would certainly require heroic measures to attract private investors, ranging from major electricity price reform to institutional restructuring. In the next decade or so, however, such steps are likely to appear slowly and with great difficulty, and even then they may not be sufficient to meet electricity service needs through supply-side investments alone.

3.1.2 Environmental implications of additional electric power generation

For the global community, an additional concern is that further electric power generation in developing countries and Eastern Europe may, depending on the energy sources utilized, contribute to undesirable environmental changes. With respect to global climate change, the most widespread concern, the basic situation is well-known. Although economic activities in industrialized countries have accounted for most of the increases in concentrations of carbon dioxide (CO_2) and other 'greenhouse gases' in the Earth's atmosphere since the 18th Century, developing countries are expected to account for most of the increases in greenhouse gas emissions over the next century.

Already, developing countries account for most of the deforestation that is occurring, and they are expected to represent most of the growth in fossil fuel use in the foreseeable future. Even now, China ranks third (behind the USA and the USSR) in CO_2 emissions from fossil fuels; India is the seventh largest in emissions, and Poland is eighth. In terms of net carbon emissions from land-use changes, in 1980 Brazil accounted for nearly one-third of the global total, five developing countries represented about half (Brazil, Indonesia, Colombia, Ivory Coast, and Laos), and developing countries in Amazonia, Southeast Asia, and Central Africa as a group represented more than 95% of the total. As the global total of carbon emissions has risen in recent decades, the developing country share has also risen (Fig. 8).

But the more serious concerns are about the future. For example, the World Bank survey of the electric power sector plans of 70 developing countries, mentioned above, indicates that half of the additional 384 GW of electricity generation capacity during the 1990s, will be based on coal — equivalent to about half the total current USA coal use for electricity generation added to the global total in one decade [4]. As another example, the projections of future energy supply and use prepared for the 1989 World Energy Conference suggest a doubling of global coal use by 2020 (in the moderate growth case), with all of the increase occurring in the Third World and Eastern Europe [2].

As with the current picture, the future plans of developing countries are dominated by the activities of a relatively few countries. For instance, about 70% of the planned coal use reflected in the World Bank figures for the 1990s will take place in China and India. Regardless, the implications are sobering. China's Environmental Protection Agency estimates that their country now accounts for about 7% of global greenhouse gas emissions; by the year 2100, they estimate that China will account for 28% of the global total [16].

Figure 9 indicates the general expectation: CO_2 and other greenhouse gas emissions from the industrialized world leveling, emissions from the USSR and Eastern Europe growing moderately, and emissions from the developing countries growing more rapidly as development proceeds. In these projections, shortly after 2000 the developing countries become the largest contributor to the global total, and thereafter their rising curve becomes the main reason that the Earth's total emissions keep climbing.

The main significance of this picture is that developing countries can expect growing pressures to reduce their rate of increase in using coal and perhaps oil to provide energy for development. This process is likely to range from efforts to negotiate international agreements along the lines of the Montreal Protocol on reducing CFC emissions to efforts to curtail international public-sector financing of fossil-fuel facilities. Irrespective of the current positions of individual governments in the industrialized world, if the evidence continues to grow that climate change is a legitimate concern, the future is clear: widespread use of coal and other high-impact fossil fuels in developing countries is going to face growing political and financial impediments, regardless of development needs.

3.2 The attractiveness of efficiency improvement as an alternative

At the same time that power system expansion plans based on supply-side additions – especially coal and large-scale hydroelectric power – are coming under greater scrutiny, efficiency improvement is getting new attention as an attractive alternative. Not only are analysts making a case for efficiency improvement; but the success experiences of industrialized countries since 1974 seem compelling; and it is clear that new technologies for electricity supply and use are more efficient than many being used in developing countries at this time. At least as important, there have been a growing number of successes with efficiency improvements in developing countries in recent years.

4. OPPORTUNITIES FOR ELECTRICITY EFFICIENCY IMPROVEMENT

The opportunities for improving the efficiency of systems that provide electricity services – from electricity generation to end use – are indeed impressive, not only in industrialized countries but in developing countries as well. Much of the current information about potentials in developing countries is in fact fairly recent, stimulated by recent successes with energy conservation in industry, the impending electric 'power crisis' in developing countries, and the important 'thought experiment' of Goldemberg, Johansson, Reddy, and Williams [17, 18, 19, 20], who have shown that technologies are readily available to improve efficiencies by margins many people had previously thought fanciful.

The most important breakthrough has been understanding that electricity supply and use is an integrated system, from fuel consumption through electricity service consumption, and that efficiency potentials should be considered in every part of the system when investment alternatives are weighed. Components of this system include electric power generation, transmission and distribution, load management, and electricity end use. For instance, the A.I.D. power crisis study estimated that generating plant efficiencies in developing countries could be improved by an average of 10 to 20%, transmission and distribution losses from about 25% to 15-20%, and end-use efficiencies by 20-30% [3]. If so, generating capacity requirements would be reduced from 1950 GW to 1150 by the year 2005 (in the mid-range scenario), and capital requirements would be reduced by US $1.4 trillion over 20 years. Since that study, the most systematic examination of such potentials in a particular country or region has been the Central American Power Sector Efficiency Initiative, designed by Alvaro Umaña, until recently the Minister of Energy, Costa Rica, and supported by A.I.D. This study is documenting impressive accomplishments as the result of a combination of local initiative and external support.

4.1 Electricity generation

First of all, in many cases electricity can be generated more efficiently. Not only is it possible to improve the availability of current electric power plants in many developing countries much more cheaply than building additional plants, it is often possible to produce more kilowatt-hours per unit of energy consumed in power generation. For example, even though the power generation system in Costa Rica is relatively efficient by the standards of developing countries, the study now under way indicates that biomass-fired steam-injected gas turbines (BSTIG) are considerably more efficient (economically) than advanced simple cycle combustion engines, medium-speed diesel engines, and other technologies currently in use and/or under consideration (Fig. 10). Energy efficiency advantages are less clear, unless the biomass fuels for electricity would otherwise be used less efficiently. But it is quite clear that, in most developing countries, power generation technologies can be managed more efficiently, raising both energy and economic efficiencies; in fact, a major current World Bank research project is looking specifically at ways to improve electric utility performance in this respect [21]; also see [22]. In addition, power plant efficiency can often be improved substantially by investing in rehabilitation.

4.2 Transmission and distribution

It is also possible in a great many cases to improve the efficiency of electricity transmission and distribution (T&D). Losses in T&D systems are usually characterized as 'technical' (energy lost within the system due to heating, resistance, or other physical causes) or 'nontechnical' (energy which reaches users but for which the electric utility is not paid). Total losses in developing countries often exceed 30%, compared with attainable levels of about six% [23]. For instance, Table VII shows T&D loss data for the 14 utilities of the Colombian power system; average losses total 19.8% – mostly technical losses in distribution systems. Significant improvements are possible in developing countries, often fairly quickly; for example, Costa Rica has already reduced overall system losses to 11%. Besides the use of such standard approaches as increasing the size of conductors, adding capacitor banks, and replacing transformers, newly-emerging technologies for power system components, power electronics, and improved power quality (especially important for many state-of-the-art electricity end uses) offer the prospect of even further efficiencies [24].

4.3 Load management

In addition, the process of load management can often be made more efficient, reducing both energy and economic costs of meeting seasonal and shorter-term peak loads. As one example, a recent demonstration project in Costa Rica investigated a combination of tariff modifications and the dissemination of information and technical assistance to users regarding a variety of load control measures in order to determine how much power generation could be saved. In this test, 24 participating customers with a coincidental peak demand of 21 MW reduced their peak demand by 3 MW, or 14%, at costs to the customers averaging a payback period of two months and costs to the utility of only about US $11,100 compared with estimated annual savings of nearly US $200,000 [25].

Table VII Percentage Loss Data From 14 Colombian Utilities, Circa 1982

Loss of Category	Percentages				
	Minimum	Average	Maximum	Average Minus Minimum	Maximum Minus Maximum
Transmission system (technical losses)					
Transmission lines	0.2	2.0	3.5	1.8	3.3
Subtransmission lines	0.1	1.1	1.6	1.0	1.5
Transformers	-	0.9	-	-	-
Corona effects	-	0.8	-	-	-
Distribution system (technical losses)	.9	2.7	7.4	1.8	6.5
Primary distribution feeder	1.5	1.9	2.3	0.4	0.8
Distribution transformer	2.4	4.0	6.3	1.6	3.9
Secondary distribution feeders	- 0.1	1.1	3.4	1.2	3.5
Decalibrated meters					
Non-technical					
Illegal decalibration	0.1	0.9	2.1	0.8	2.0
Damaged meters	0.2	0.6	6.8	0.4	6.6
Incorrectly estimated consumption	0.0	0.9	1.6	0.9	1.6
Theft and bypass	1.8	0.9	13.5	1.1	11.7

Source: CESPEDES, R.

4.4 Electricity end-use

Finally, although the disaggregated nature of the 'market' makes data more elusive, the efficiency of electricity end uses can be improved: in space heating, cooling, and ventilation; refrigeration; lighting; electric motors; and other uses. Goldemberg et al. describe a wide range of promising technologies; for instance, preliminary analyses in India suggest that replacing high energy-use incandescent lamps with compact fluorescents would meet demands for lighting at a cost of conserving electricity which is one-fifth the cost of equivalent supply [26]. Analyses from Costa Rica (still under way) indicate that cost-effective efficiency improvements in the residential and commercial sectors are possible in electric stoves, refrigerators, lighting, and water heating – amounting to total potential electricity savings (with 100% market penetration of more efficient devices) of about 380 GWh per year [27]. Detailed evaluations of efficiency improvements in other countries are also encouraging. For example, a study by Schipper in Indonesia has concluded that electricity use in that country for appliances (such as refrigerators, air conditioners, washers, water heaters, ovens, and lighting) could be reduced by 25 to 35% without raising the price or reducing the level of electricity service provision [28].

Given a significant rate of economic development, however, the main potential for efficiency improvement in developing countries lies not in equipment retrofits but in the process of technology choice for future activities. Without such development, the cost of retrofits is likely to be unacceptable to most energy users. With development, on the other hand, both the opportunities for improving the efficiency of the equipment stock (i.e., the rate of capital stock replacement) and the resources for making the necessary investments are increased. Development is good for efficiency improvement, just as efficiency improvement is good for development.

4.5 Summary

These opportunities do not necessarily mean that efficiency improvement is the best power system investment option in every case. Sometimes, especially when a developing country has attractive renewable or natural gas resources available domestically and projected electricity needs are large, some supply-side investments will promise better returns than some efficiency-improvement investments. But it is increasingly clear that electric power system planning should consider the entire range of investment possibilities for increasing electricity services (often called 'least-cost planning') and that, when this occurs, efficiency improvement will very often show the best returns per currency unit invested. Figure 11 summarizes schematically the possible implications of an integrated least-cost investment program.

5. EXPECTATIONS FOR EFFICIENCY IMPROVEMENT

The question, then, is not whether electric power systems, including end uses, can be made more efficient in developing countries, usually delivering additional electricity services more cheaply than by adding supply capabilities at current levels of efficiency. The question is how much efficiency improvement can realistically be expected to occur – and under what conditions. Clearly, technological feasibility alone is not enough to assure efficiency improvement; otherwise, the power systems of developing countries would be far more efficient than they are at present. Just as clearly, the achievements ahead will depend partly on how actively the opportunities are pursued.

5.1 Obstacles to electricity efficiency improvement

Even though efficiency improvement seems to make sense in a great many situations, achieving its potential requires overcoming a number of very real constraints (some characteristic of <u>any</u> country, industrialized or developing; some more characteristic of developing countries) [29].

<u>5.1.1 Inherent constraints on energy efficiency improvement</u>

We know from our own experience in the USA and the rest of the industrialized world that many potentials for energy efficiency improvement are difficult to realize. Consider, for example, the substantial potential for efficiency-improving technology retrofits in multifamily housing units; here, adoptions in the USA have fallen far short of what appears to be the social optimum. Some of the constraints on efficiency improvement in such cases appear to be virtually universal; e.g.:

(1) Equipment already bought will normally be used. Clearly, a rational energy user will not necessarily replace a refrigerator or an electricity-powered motor as soon as a more efficient alternative becomes available. He or she will continue to operate the current equipment as long as the costs of operation are less than the savings from

improved efficiency. As a result, less-efficient equipment will coexist with advanced equipment while the current capital stock ages – a constraint in the short term on technology replacements (but less of a constraint for a growing economy or for technologies with short lifetimes).

(2) Consumer preferences are complicated and multidimensional. We know that potential energy technology adopters do not always make the technology choice that an analyst considers optimal. In most cases, the reason is not that the decision-maker is irrational but that the analysis is too narrow to capture all of the characteristics considered in making technology choices – especially where the analyst comes from a different cultural context from the one being analyzed. Uncertainties about new technologies and future economic conditions can also encourage consumers to be cautious.

(3) Consumers may use improved efficiencies to buy more energy services rather than to reduce supply requirements. We know that cost reduction is not the foremost goal of every consumer. For instance, a poor family may choose to invest the savings from efficiency improvement in increased comfort and convenience. Such 'take-back' effects can mean that energy supply requirements do not drop as much as predicted – because the quality of life of some consumers has been enhanced (a contribution to development, even if not to reductions in energy requirements).

5.1.2 Additional constraints on energy efficiency improvements in many developing countries

In many developing countries, however, these kinds of 'normal' constraints are dwarfed by local conditions that undermine efficiency-improvement efforts from the outset. Although the particular problems may vary considerably from country to country, the most common – and the most serious – are the following:

(1) Energy prices do not send the right signals. In a great many developing countries, energy prices are set by government action at levels that do not reflect the true costs of providing energy services. In other words, prices set too low do not adequately or appropriately encourage energy efficiency improvements, while at the same time the energy services are provided by an inefficient supply and use system at a loss to the national economy. Even though price reform can appear politically hazardous, no single factor is as important in motivating efficiency improvements as energy prices; where prices are artificially low, the prospects for improvements are lower.

(2) Other government interventions in economic markets also reduce incentives for efficiency improvement. Certain policy conditions in developing countries often create barriers to efficiency improvement. For example, other things equal, market competition encourages more efficiency in production, including the use of more efficient energy-using equipment. Restrictions on competition therefore tend to reduce the adoption of efficiency improvements. As another example, high tariffs on imports of efficient equipment also discourage improvements. In a policy environment where such conditions undermine voluntary individual decisions, efficiency improvement must be pursued through extraordinary external interventions, piece by piece, rather than through a general structure of incentives. It is unrealistic to expect as much to be accomplished this way [30].

(3) Effective institutions are lacking to get some of the job done. In order to realize potentials for efficiency improvements in developing countries, institutions will be

needed to mobilize resources and accomplish complex tasks. But in most developing countries, responsibilities for improving energy efficiency are fragmented, and end-use efficiency is typically no one's job. Furthermore, many key energy-related institutions are ineffective in reaching their goals, however defined, at least partly because of a shortage of skilled managerial resources.

(4) Financial resources are lacking to support investments in energy efficiency improvement. Even when effective institutions are available in some connections, it can be difficult to find investment capital to support efficiency improvements in developing countries. For instance, many countries are close to the limit of their borrowing power, especially for the power sector. In addition, to many lenders efficiency improvement is a less conventional, more diffused target for lending than supply-side energy facilities. And the developing world in general tends to lack mechanisms to finance efficiency improvements at a small scale: e.g., by small industry, commercial firms, and the residential sector.

(5) Future economic conditions can be highly uncertain. In most developing countries, the economic planning horizon is very short, partly because the growth process is fragile but also partly because the political economy can be destabilized so easily. It is not uncommon, therefore, to see investment payback requirements of two to three years or less – which implies a higher discount rate than the usual assumptions in estimating potentials for efficiency improvement. Where this is true, it is not realistic to expect as rapid and as widespread an adoption of efficiency-improving technologies as would be the case with lower discount rates.

(6) Key decision makers are often unaware of both the need and the potential for energy efficiency improvement. Finally, decision-makers in developing countries have plenty to worry about, and energy inefficiency is frequently too far down their list of worries to get much attention. As a result, efficiency improvement tends either to be ignored as a policy priority or to be accepted passively as a target of external resources. Unless efficiency improvement in a developing country is grounded in local will and determination, however, the implementation of good ideas is almost certain to lag.

5.2 A summary of reasonable expectations

Clearly, then, efficiency improvement depends on more than engineering-economic feasibility alone. As indicated above, the available evidence suggests that it depends on an effective combination of three sets of factors: characteristics of technologies, economic incentives, and institutional structures. Deficiencies in any one of the sets can undermine the entire enterprise, but strengths in one can help to compensate for weaknesses elsewhere. For example, a particularly attractive and well-suited technology can sometimes overcome problems with organizations and incentives, while strong organizations and appropriate incentives will eventually cause the right kinds of technologies to emerge. In general, however, progress in the near term requires some strengths in all three. Developing countries vary widely in this respect, but most of them are faced with barriers in at least one of the three categories.

Even with these barriers, many efficiency improvements will certainly take place; the forces are already in motion – economically competitive technology options, capital constraints on supply-side initiatives, shifts in the orientation of public-sector lending, etc. But far more of the potential can be realized if policy interventions are introduced to encourage energy efficiency improvement: technology development and adaptation to make the technologies cheaper, more reliable, and otherwise more attractive in developing country markets; interventions in the economic system to improve the operation of energy-related markets; and improvements in institutions to increase their capabilities for reaching organizational objectives. If effective policies are not introduced in most countries, the savings between now and, say, 2020 are more likely to be in the 20 to 30% range (compared with a business-as-usual scenario) than the 50% or more which appears to be economically attractive. Even these more modest savings, of course, are significant and encouraging. On the other hand, if policy initiatives reinforce the potentials that we know can be brought to bear, the possibilities are profoundly important, both in terms of the efficiency levels that can eventually be reached and the rate at which those levels can be approached.

This tends to redirect attention away from the efficiencies of technologies alone toward the efficacy of public policies and the likelihood that effective policy initiatives will be pursued. In the end, it will be these issues that will determine how much efficiency improvement is accomplished in most developing countries [29].

5.3 An example of an initiative to promote efficiency improvement

One example of an effort to catalyze such policy initiatives – in a cooperative spirit between developing and industrialized countries – is the Global Energy Efficiency Initiative (GEEI), stimulated in the USA by A.I.D. but including a variety of other parties as well. This initiative has emerged from deliberations within an ad hoc working group, involving individuals from three USA federal agencies and the Office of Technology Assessment of the USA Congress, two multilateral development assistance agencies, several environmental and energy conservation public interest groups, a private-sector trade association, and several research and consulting institutions [7]. The aim is produce an agenda for action that can be offered to a wide variety of parties as a basis for discussion, without requiring an official stamp of approval from any particular organization.

Although the details of GEEI are still being shaped, the initiative is expected to propose at least five kinds of activity in developing countries and Eastern Europe, supported at least in part by industrialized countries and multilateral institutions: prototype country-specific energy efficiency improvement projects, institution-building, training, information dissemination, and financial assistance. The current estimate is that cost effective investments in energy efficiency improvements could globally reduce greenhouse gas emissions by about 25% by the year 2025, besides contributing to the economic development process. One key will be to focus on a limited number of countries, rather than spreading the effort thinly across scores of countries worldwide. Obviously, opinions differ about the countries that should be emphasized; but most lists agree on China, India, Brazil, Eastern Europe, and Southeast Asia as high priorities [31].

5.4 Putting electricity efficiency improvement in context

It is essential, however, not to focus on energy efficiency improvement to the exclusion of basic development concerns. An old saying in the USA suggests that: 'if all I have is a hammer, all the world looks like a nail.' What we seek are improvements in the quality of life of the world's population, and energy services are merely a means to this end.

Energy requirements are in fact complexly related to economic and social growth. For example, energy supply requirements depend on economic and population growth as well as achievements with efficiency improvement. At the same time, as indicated above, the prospects for energy efficiency improvement are better in a high-growth environment, where new capital stock is being added more rapidly and more investment resources are available; and energy efficiency improvement contributes to economic growth by freeing capital resources for other purposes. In other words, efficiency improvement contributes to growth, which means additional requirements for energy services – with implications both for supply systems and the market penetration of further efficiency-improving technologies.

6. CONCLUSIONS

It seems quite clear that, in most developing countries, investing in improving the efficiency of electricity service provision is at the margin the most cost-effective way to expand electricity services in order to advance social and economic development, in spite of a policy environment that often puts efficiency improvement at a disadvantage. It is not quite as clear, however, how much efficiency improvement can actually be accomplished in developing countries over the next several decades. The main reason is that realizing its full potential will call for wrenching redirections by many industrialized countries, developing countries, and multilateral institutions – ranging from energy price reform to major changes in financial and technical assistance policies.

In the meantime, it is illusory to think that efficiency improvement will obviate the need for investments in electricity supply facilities entirely. Rather, if we are both determined and fortunate, efficiency improvement may be able to reduce the investment requirements for new supply facilities to a level that is feasible for most developing countries, avoiding a situation where energy conditions limit development itself. In this process, efficiency improvement can also significantly ease pressures on the global environment, especially if it makes real headway in the developing and Eastern European countries that plan to emphasize coal for future electric power generation. Either of these by itself would be a worthy goal. Together, they are compelling reasons to do as much with efficiency improvement as we can.

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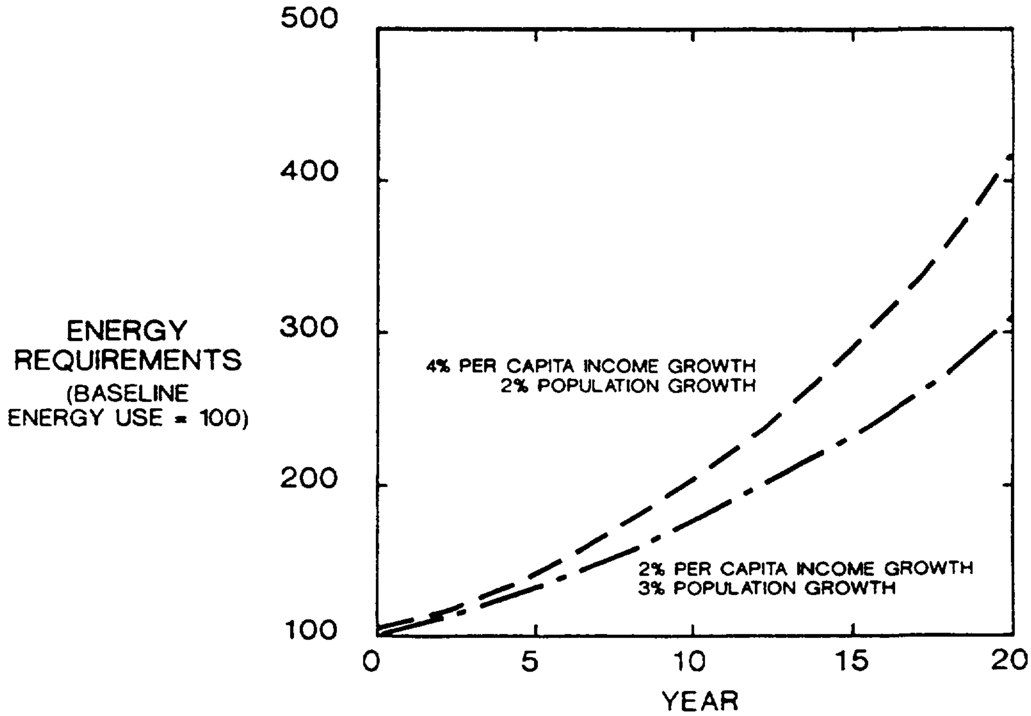


Fig. 1 Energy requirements for development

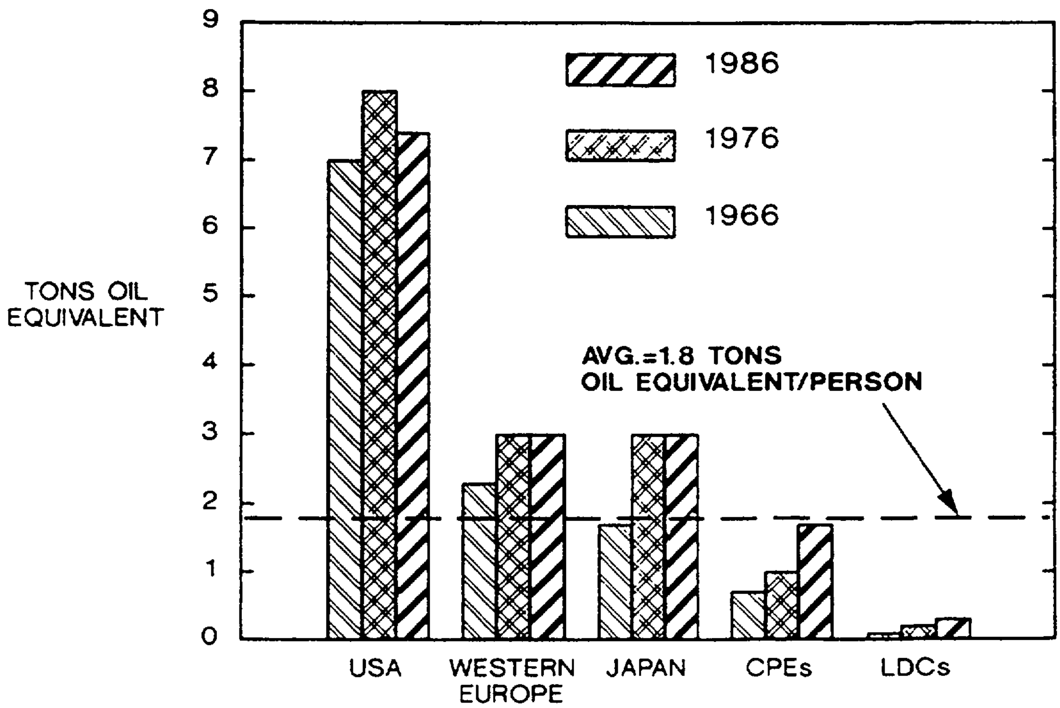


Fig. 2 Per capita energy consumption

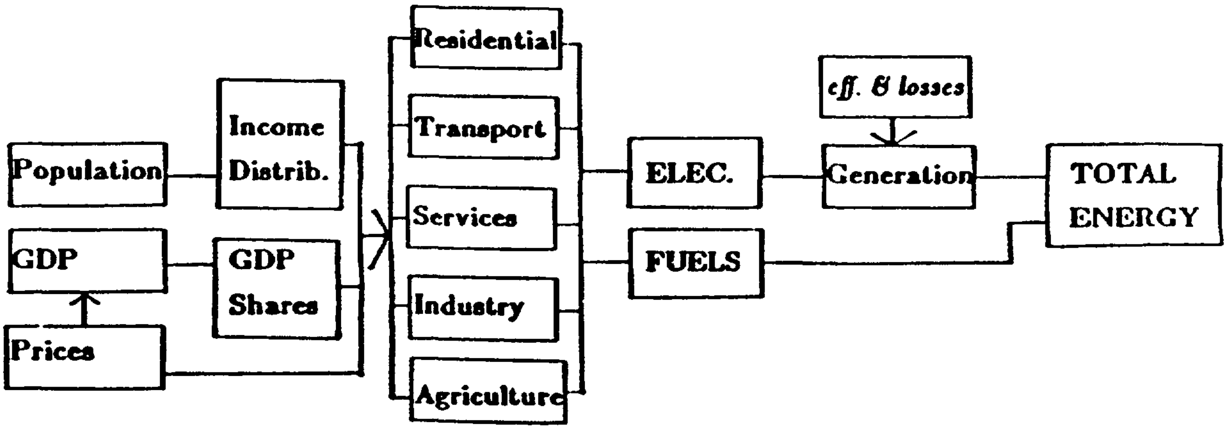


Fig. 3 LDC energy scenarios: approach for estimating regional trends (LBL, 1989)

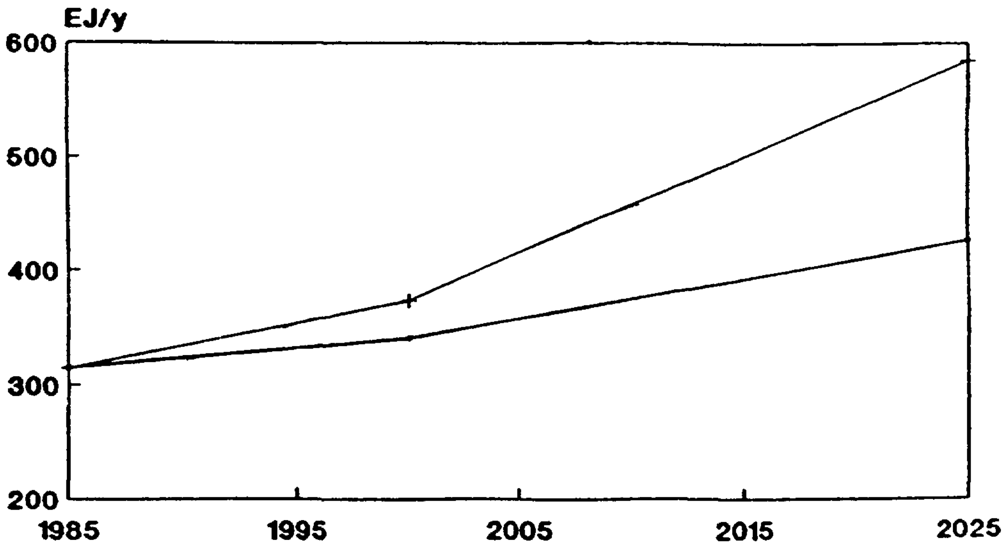


Fig. 4 Primary energy worldwide (excluding non-commercial energy)

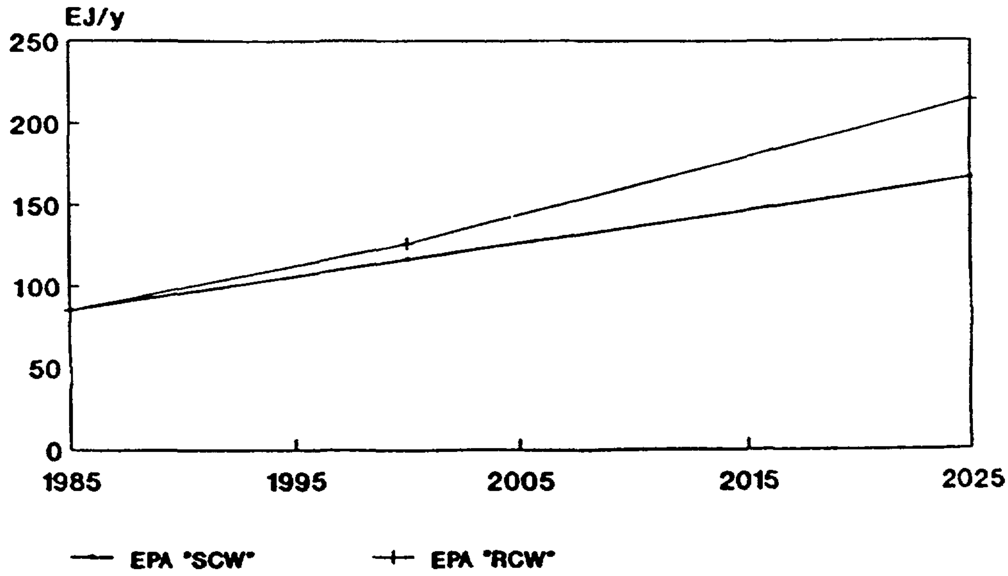


Fig. 5 Primary energy for developing countries (excluding non-commercial energy)

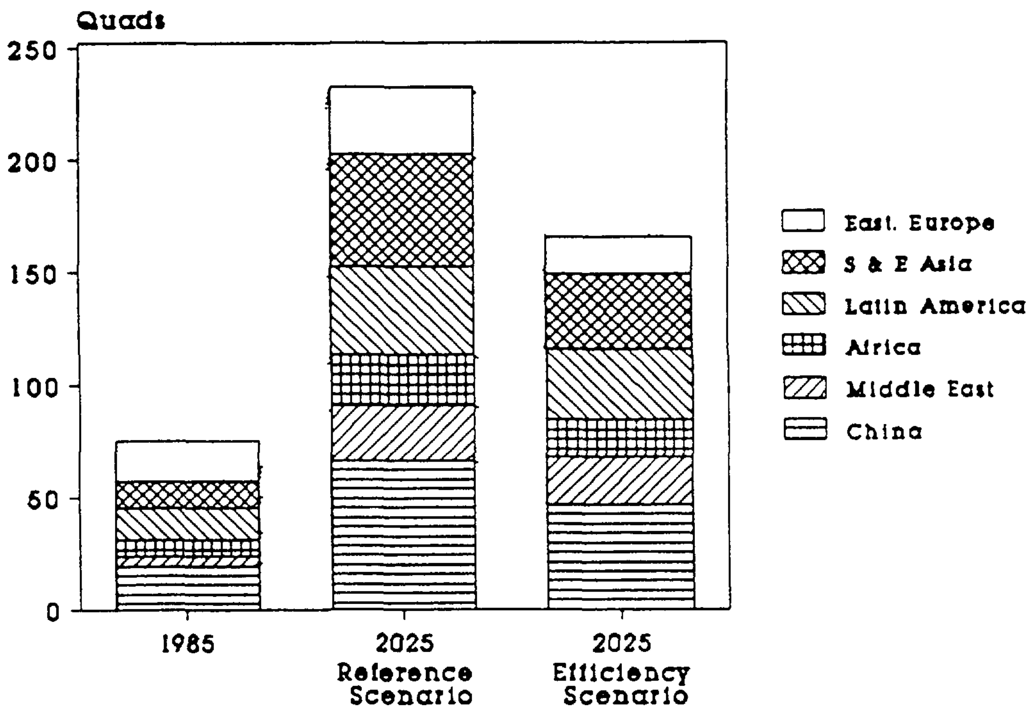


Fig. 6 Primary energy consumption by region, LDC's and Eastern Europe

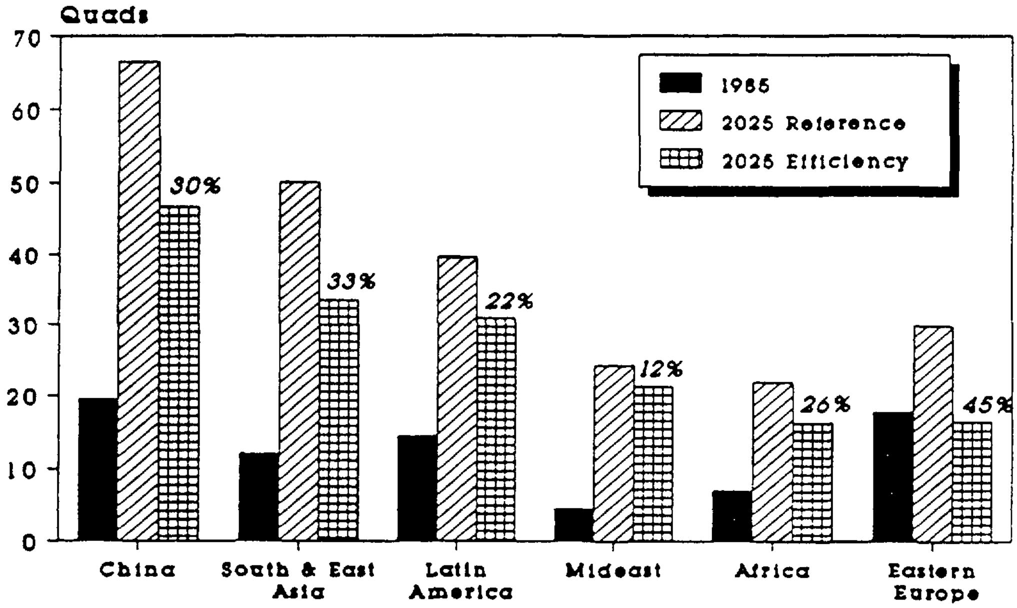


Fig. 7 Primary energy consumption scenarios, LDC's and Eastern Europe (with savings in percent)

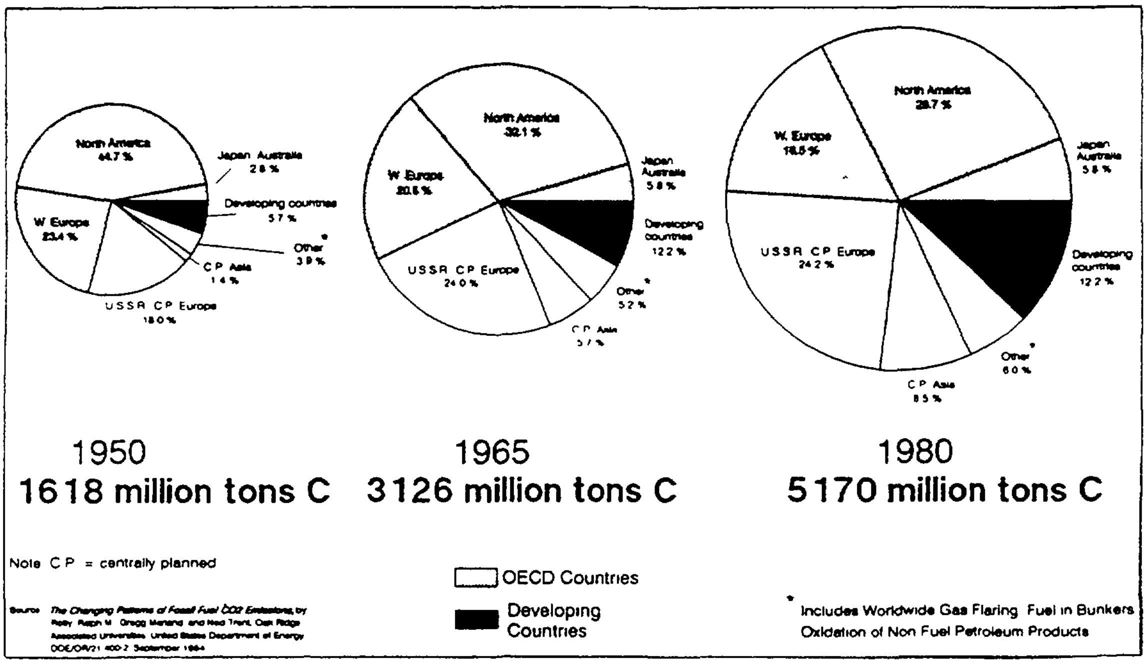


Fig. 8 Recent changes in global carbon dioxide emissions

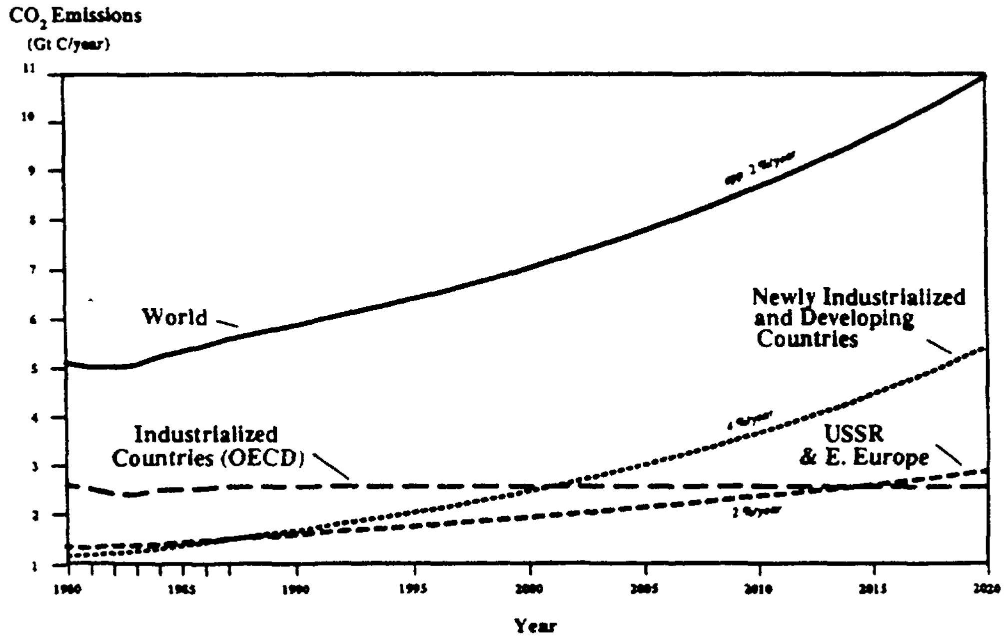
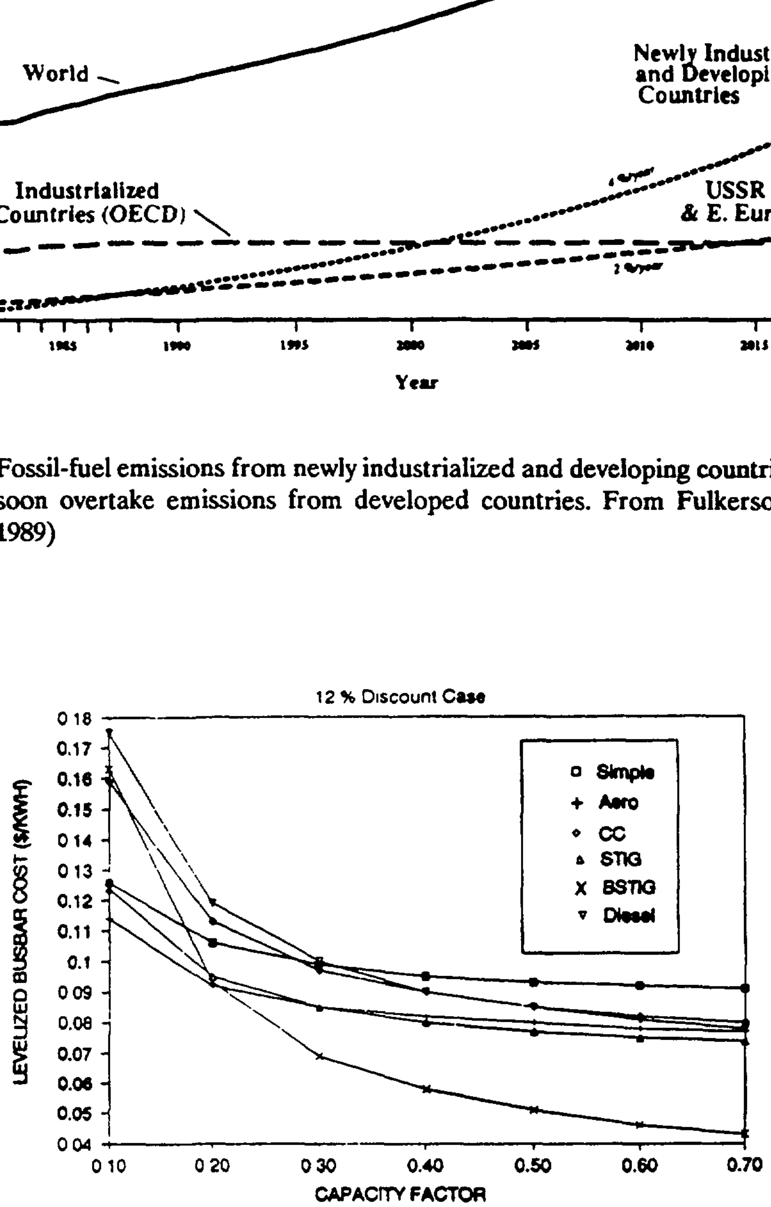


Fig. 9 Fossil-fuel emissions from newly industrialized and developing countries could soon overtake emissions from developed countries. From Fulkerson et al., 1989)



Assumptions: 12% discount factor; $6.7/MBtu distillate; $1.73/MBtu bagasse cost; includes M&O costs; fuel costs, & captial recovery costs (30yr life).

Fig. 10 Relative costs of electric power generation technology alternatives in Costa Rica

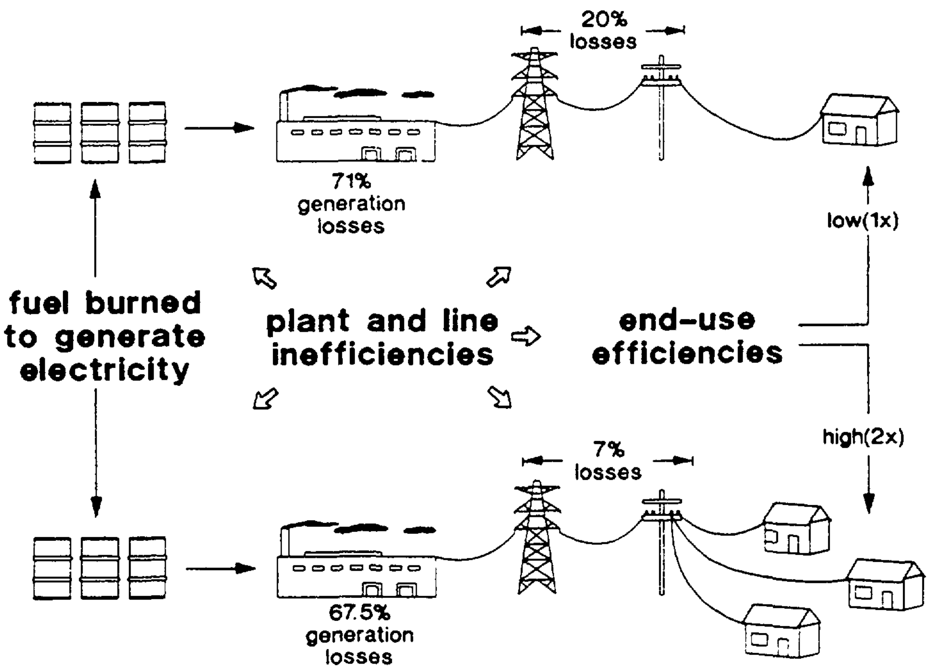


Fig. 11 Schematic diagram of the implications of power system efficiency improvement in developing countries

THE OUTLOOK FOR ELECTRICITY EFFICIENCY IMPROVEMENTS IN THE UNITED STATES OF AMERICA

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ABSTRACT: Since the mid-1970s, efficiency improvement has contributed more to the expansion of electric power services to USA consumers than any supply source. Further improvements are expected in the next several decades, as improved technologies move into more extensive use. Normal market forces are likely to improve efficiencies of electricity production and use by 10-15% or more by 2010, and changes in policy conditions could realize savings of 30-50% with energy-efficient technologies that are already available.

1. INTRODUCTION

Since the early 1970s, the efficiency of electricity production and use in the USA has increased more than any objective observer twenty years ago would have thought conceivable. This does not mean, of course, that still further improvements are not possible; but efficiency improvement has already contributed more in the past decade and a half to the expansion in electric power services to the USA consumer than any single supply source. The degree to which this trend will be continued in the next twenty years or so, however, will depend more on evolving policy conditions than on current and expected technology potentials.

2. AN OVERVIEW OF ELECTRICITY DEMAND IN THE USA

For most of the Twentieth Century, electricity has been a major contributor to social and economic development in the USA. Along with liquid fuels from petroleum, it has helped to bring about profound transformations in ways of life and standards of living, including what has been called a democratization of energy services – no longer just the province of large firms and personal wealth, but as near an individual consumer as an electric power outlet a few meters away [1, 2].

At this point, most USA electricity is produced from coal (about 47% in 1988: Fig. 1), with total generation totaling 2,701 billion kWh in 1988. Consumption in that same year was 2,566 billion kWh, including about 35 from power imports; overall net losses were about 5%.

Electricity consumption is relatively evenly distributed in the USA among residential, industrial, and commercial uses, with residential and commercial uses growing fairly steadily while industrial uses leveled between the mid-1970s and mid-1980s (Fig. 2). In 1986, in fact, consumption by residential electricity users exceeded industrial consumption for the first time in USA history. The aggregate rate of growth between 1979 and 1986 was less than 2%/year, compared with rates in the late 1960s and early 1970s in the 6-9%/year range. In 1987 and 1988, total consumption rose about 4½%/year, at least partly because electricity prices for most consumers stopped climbing while the economy stayed strong (Fig. 3).

As with most other countries, the general outlook for the future is pervaded by uncertainties. Clearly, electricity will continue to increase its share of total energy end-use in the USA; the USA Energy Information Administration projects electricity consumption growing by 2.1-2.6%/year for the next 20 years. If demand grows faster than this, some regions of the country could develop supply shortages, in spite of new flexibility in arranging power imports and/or purchases of power from non-utilities. For example, according to the North American Electric Reliability Council, the USA needs 73 GW of new generating capacity to meet anticipated demands in 1997 [3]. But utilities remain cautious about adding major new generating capacity, because demand growth rates of 2% or less could leave them with expensive excess capacity. Such uncertainties make efficiency improvement a key part of electricity sector contingency planning as well as normal operations.

3. ENERGY AND ELECTRICITY EFFICIENCY IN THE USA

The USA has improved the efficiency of its energy use significantly since the 1973 oil embargo. In the period 1974-88, total national energy use increased by 8%, while gross national product increased by 45%, which means that the country now uses 26% less energy to produce one dollar's worth of goods and services, saving the country at least $21 billion in the cost of new power plants [4]. Although some of this reduction can be attributed to structural changes in the economy, most of it has been the result of increases in energy efficiency [5]. Electricity efficiency follows the same general pattern as overall energy efficiency.

This does not, of course, bring energy efficiency in the USA to the levels of European countries and Japan. Per capita energy consumption remains more than twice as high, partly due to industrial structure and way of life but partly because of efficiency differences in energy technologies. But for a country traditionally characterized by a 'psychology of abundance' [6, 7], the accomplishments of recent years have been impressive and encouraging.

This record of success, at least by American standards, is a function of five main factors (e.g., [8]).

(1) Technology advances, which have revolutionalized systems for converting electricity generation into electricity services [3, 8].

(2) Price increases, which account for more than half of the country's energy efficiency improvement since 1973 [9]. Electricity prices have risen by as much as a factor of three or four (Fig. 3), in current dollars, with the climb especially sharp in the 1974-1983 period. No single factor has done more to direct consumer attention to the potential benefits of efficiency improvements than this.

(3) Government programs, which have been especially important at the federal level in improving technology alternatives through R&D and at the regional level in challenging traditional supply-side utility expansion strategies. Probably most important was the unwillingness of regional public utility commissions in the late 1970s to pass through rising fuel costs for electric power generation to the consumers through electricity rate increases, which forced significant changes in the directions of electric utilities – including a new willingness to consider the merits of investing in energy efficiency improvement programs.

(4) Electric utility responses, which have shown surprising flexibility and entrepreneurism in coping with changes in the policy environment. With this stimulus, many utilities (once considered among the least adventurous of all the sectors of the USA economy) moved in new directions with gusto – from cooperation in power plant construction to new roles in wheeling electric power from region to region and even diversification into other lines of business. Several utilities became recognized leaders in implementing efficiency improvement strategies, including free energy audits and time of service pricing; and, in sections of the country where public opinion continues to support efficiency improvement programs, they continue to be innovative.

(5) Private sector initiatives, ranging from cogeneration to offering energy efficiency improvement services, reflecting a discovery that energy conservation can be good for business. A profound psychological change in the USA economy took place in the late 1970s, when the USA private sector began to recognize that 'zero energy growth' could mean business opportunities and increased profits rather than economic controls. With the help of price

> increases and new government programs (such as efficiency standards), American businesses started competing in the interest of efficiency improvement, both in their internal energy-use decision-making and in trying to identify and expand the markets for their goods and services. This has probably been the main force sustaining through the 1980s the efficiency improvement trends begun the 1970s.

In 1990, electricity efficiency in the USA may be slowing in its rate of improvement, even though many of the current efficiency levels are still well short of what seems economically and socially desirable. Some further efficiencies will certainly be achieved; for example, Carlsmith et al. [5] forecast a 12% improvement in overall energy efficiencies in the 20 years to 2010 due to normal market forces in the USA (1990), and the Electric Power Research Institute (EPRI) forecasts improvements of 8.5% by 2000 due to anticipated changes in energy marketplace ([3]: Table I)[1]. But both the burst of technological and institutional creativity sparked by the energy 'crises' of the 1970s and the price increases of that period may be running out of steam (so to speak); and some observers believe that the E/GDP ratio is more likely to stabilize in the 1990s than to continue to drop – barring some kind of sharp change in conditions.

Efficiency improvement initiatives continue, however, in a number of individual cases. Electric utilities in the USA sponsor more than 1300 demand-side management programs, and EPRI estimates that these programs have the potential to reduce supply requirements by the year 2000 by the equivalent of 45 GW [3]. As one example, a Massachusetts electric utility is responding to consumer concerns about the high front-end costs of high-efficiency fluorescent lighting technologies by leasing the more-efficient light bulbs, with payments included with monthly electricity bills, and the results are reported to be encouraging.

4. CHALLENGES IN IMPROVING ELECTRICITY EFFICIENCY

In any event, most observers agree that electricity efficiency in the USA can still be improved substantially in the next 20 to 30 years – far beyond what is considered most likely to happen. Goldemberg et al. [10] for example, have suggested that per capita final <u>energy</u> consumption in the USA can be cut nearly in half by 2020 with a 100% increase in per capita GNP, if the most efficient available technologies are used [10][2]. This would include a slight increase in total <u>electricity</u> use from 7.6 EJ in 1980 to 9.1 in 2020, while the total use of other energy delivery forms drops sharply. Table II summarizes some of the potentials described in their report. Similarly, EPRI estimates that the use of the most efficient end-use technologies could save up to 44% of the electricity the USA would otherwise be using the year 2000 [4], and other estimates of maximum savings range as high as 75% [8, 11]. Potentials appear to be especially bright for improvements in the efficiency of lighting, electric motor systems, and cooling/refrigeration.

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[1] These forecasts are focused on end-use efficiency improvements -- not considering efficiency improvement potentials in electricity generation, transmission and distribution, and load management. This means, of course, that in terms of national aggregates they can be considered relatively conservative

[2] By contrast with Carlsmith et al [5], these estimates include potentials for efficiency improvement on the supply side.

Table I Estimates of Efficiency Improvements Attributable to Regulatory Mandates and Changes in the Energy Marketplace in the Year 2000[1]

Sector/End Use	GWh	Percent
Residential		
Refrigeration	51,158	28.7%
Central air conditioning	30,920	22.8%
Freezer	22,206	37.1%
Water heating	12,830	7.6%
Space heating	9,783	3.9%
Lighting	6,613	5.0%
Cooking	3,628	7.3%
Room air conditioning	2,905	17.5%
Dishwashers	948	3.9%
Residual appliances	[2]	[2]
Total	140,991	10.7%
Commercial		
Lighting	32,190	10.0%
Heating	11,933	8.3%
Refrigeration	8,193	8.9%
Ventilation	[2]	[2]
Water heating	[2]	[2]
Cooking	[2]	[2]
Miscellaneous	[2]	[2]
Total	52,316	4.7%
Industrial		
Motor drives	77,564	8.5%
Lighting	42,182	25.8%
Process heating	8,677	6.1%
Electrolytics	954	0.6%
Other	[2]	[2]
Total	129,377	9.4%
TOTAL	322,684	8.5%

Note: [1] Versus load growth efficiency levels frozen.
[2] Negligible

The problem, of course, is that under current conditions in the USA, existing cost-effective technologies are likely to remain unused in many cases – or to move into use relatively slowly. One very recent study [5], conducted for the USA Department of Energy's National Energy Strategy, lists the following barriers to efficiency improvement [12-16 also see 4] in the USA, which are more problematic in some regions of the country than others.

Table II Potential Changes in U.S. Electricity Use[1]

	Percentage Growth in Activity, 1980-2020	Annual Electricity Use, in Exajoules	
		1980	2020
Residential and commercial sector (selected examples)			
Space heat	303	0.29	0.19
Air conditioning (central)	281	0.24	0.37
Water heating	166	0.33	0.14
Refrigeration	128	0.56	0.25
Industrial sector (total)	231	3.0	5.1

Note: [1] According to scenarios from Goldenberg et al., 1987, Table 16-19

4.1 Structural barriers (conditions beyond the control of the individual end-use decision-maker)

- Distortions in prices. In the USA, state public utility commissions set electricity prices, traditionally on the basis of the average cost of producing electricity. If the current average is different from the marginal cost or if it does not fully reflect all the environmental and social costs of electricity supply and use, then consumers are making energy use decisions on the basis of inappropriate price signals.

- Uncertainty about future prices. Because energy prices have fluctuated widely over the past 15 to 20 years, consumers perceive that future prices are highly uncertain. Even though electricity prices changed less than other energy price during this period, they rose substantially during the 1970s and then fell in many areas during the 1980s (Fig. 3). Recent policy initiatives related to environmental controls have added to the perception of uncertainties. Meanwhile, many end-use decision-makers – who need dependable price predictions to estimate long-term operating costs – are probably avoiding some electricity-efficient options because of their higher initial costs.

- Limited access to capital. Because many energy-efficient options are more expensive in terms of front-end capital costs, access to money at the time of purchase can be an issue. In addition, the end-user's willingness to borrow or spend for cost-saving (as contrasted with adding convenience or productivity) appears often to be limited; evidence from a wide variety of studies in the USA indicates that payback periods of two years or less are usually required.

- Government fiscal and regulatory policies. In general, governmental policies in the USA have favored supply-side energy and electricity options over demand-side options. Research and development support is one example; subsidies through tax policy are another. Especially important for electricity systems is the fact that in most cases rate structures permit electric power sales increases to be treated as earnings, while efficiency improvements are not. Recently, however, several states have revised rate structures to try to address this problem (Exhibit 1: also see [4, 8, and 11]).

- Codes and standards. Related to such issues as electric appliance efficiency, codes and standards have sometimes had a strong positive effect in the USA. But the process of setting and revising such codes is slow and complicated; and the results are often fragmented, introducing other kinds of economic inefficiencies.

- Limitations in the supply infrastructure. In many cases, the availability of efficiency-improving options is limited by such realities as a lack of people trained to support the use of new technologies and/or a lack of interest on the part of regional utilities in promoting their use. In addition, the energy service industry in the USA is still young, often lacking the resources to market and deliver its services effectively.

Exhibit 1 Innovative Approaches in the United States to Offering Incentives to Electric Utilities to Invest in End-Use Efficiency Improvement

A fundamental problem for electricity system efficiency improvement in the United States has been that electric utilities can get a financial return from selling electricity but not from saving it. In such an environment, investments in demand-side programs are only likely when they are mandated from outside.

An alternative approach is to change 'the rules of the game' for utility decisions about system expansion so that end-use efficiency improvement is somehow rewarded. Basing tariffs on measures of services provided rather than kilowatt hours sold would be preferred strategy if it could operationalized, but both conceptual and measurement problems make this little more than a dream at present. In the meantime, other (cruder) strategies are being tried, usually focused on the environmental benefits of efficiency improvement. Such strategies include:

(1) Offering a 'bonus' rate of return for energy efficiency investments. In the United States, 'public utility commissions' must approve electricity tariffs, based on their determination of a reasonable rate of return from a utility's capital investment and operating costs. A Connecticut state low allows up to an additional five percent rate of return (above that allowable for other investments) for investments in efficiency improvement. Similar programs are in effect in Kansas and Idaho.

(2) Estimating the monetary value of emission reductions from efficiency-improving investments. The California Energy Commission has proposed to estimate the value of emission reduction (in dollars per kWh) associated with efficiency improvements and such other options as urban reforestation – i.e., environmental control costs avoided. This valuation would then be used as utilities formulate their expansion plans and the public utility commission revises its pricing methodology.

(3) Establishing rules for the comparison of investment options that specify preferential treatment of efficiency improvement and other options that reduce environmental impacts of providing electricity services. For example, utilities in Wisconsin are required to accept as cost-effective any demand-side option which has benefit-cost ratio of 0.85 or higher (termed a 'fossil fuel combustion credit'). Other approaches include a percentage 'adder', increasing the cost of supply-side options or decreasing the cost of demand-side options in determining cost-effectiveness; categorizing options as low, moderate, or high in environmental impacts and adding an appropriate cost increment to higher-impact options; and estimating an 'environmental score' for each option under consideration and applying different 'adders' to the cost of each option depending on its score.

4.2 Behavioral barriers (conditions related to the end-user's decision-making)

- Attitudes toward energy efficiency. There is considerable evidence that the American interest in saving energy has declined steadily during the 1980s, even though public opinion polls still show a tendency to favor energy efficiency over increased energy production. In general, without price increases or other catalysts to trigger public concern, it appears that comfort and convenience are valued more highly than efficiency improvement [4].

- Perceived riskiness of energy efficiency investments. To many decision-makers, the front-end costs of an efficiency-improving option are certain but reductions in operating costs are uncertain; efficiency-improving technologies present a greater risk of being wrong. Even more important, decision-makers are often unsure whether a new kind of equipment is likely to introduce other kinds of risks: e.g., of unreliable performance or less attractive performance characteristics.

- Information gaps. Credible information about the performance of efficiency-improving technologies is often scarce, while energy use itself is largely invisible [17]. Home energy audits have been used as one approach to remedy this problem in the USA; but they have often had little effect on electricity-user decisions, at least partly because their results have so often been presented in a dry, quantitative, impersonal manner.

- Misplaced incentives. Finally, many end-use technology choices are in fact made by intermediaries: e.g., builders or owners of rental housing. In most cases, this leads to an emphasis on first costs rather than life-cycle costs, since it is the user of the equipment who usually pays the energy bills.

5. PROSPECTS FOR FURTHER ELECTRICITY EFFICIENCY IMPROVEMENTS

Clearly, the prospects for continuing to improve electricity efficiency in the USA depend considerably on the extent to which these barriers can be reduced or removed. Efficiencies will undoubtedly improve, because on the average the stock of available new technologies is more efficient than the capital stock in use. But the rate of improvement will almost certainly fall well behind the rate that most energy analysts think makes economic sense.

Carlsmith et al. [5] recently attempted to project both the rate of improvement under current conditions (in end-use efficiencies) and the rate that might be achieved with a politically realistic stronger effort. Table III indicates their results. Assuming that real GNP increases by about 63% between 1990 and 2010, under present conditions electricity consumption will increase by 47% in buildings and 69% in industrial production. Both of these figures include more efficiency improvement than might be apparent, because both sectors are assumed to be increasing their reliance on electricity during this period. Compared with this projection, a significant push for electricity efficiency would reduce consumption in buildings by about 14% over the 20 year period. Industrial consumption would not be noticeably affected, partly because the main efficiency improvements would be in the use of other energy forms and partly because overall sectoral efficiency improvement would in some cases accelerate shifts to electricity.

It is quite possible that the USA will do better than this. With growing concerns about the global environment, energy efficiency improvement is almost certain to get more policy attention. For example, a recent report by the American Council for an Energy-Efficient Economy proposed a national goal of 2½%/year in reducing the E/GNP ratio, which would keep USA energy consumption at roughly its current level of 80 QBtu/year through 2010 [18]; also see [4]. In addition, some reviewers of the Carlsmith et al. [5] study have suggested that electricity prices are likely to rise faster than the study assumes, which would translate into higher average efficiencies (and a slower shift toward electricity).

But the range of possible electricity efficiency futures for the USA remains wide: from a continuation or even acceleration of the improvements of the past decade and a half to a virtual flattening of the efficiency curve over the next several decades. Many analysts believe that we will in fact follow a path closer to the former than the latter, for a mix of technological, economic, environmental, and political reasons. But this may reflect our views as citizens as well as our views as scientists, since the future is as much a matter of <u>will</u> as of conditional probability.

Table III Projected Electricity Use in the United States[1]

	1990	2000	2010
Assumptions			
Real GNP (billions of 1982 $)	4217	5368	6871
Population (millions)	250 0	268 4	287 8
Where We Are Headed			
Electricity consumption QBtu)			
Buildings sector	19 3	23 8	28 4
Industrial sector	10 8	14 1	18 3
Energy intensity (all fuels)			
Residential (MBtu/household)	180	166	162
Commercial (KBtu/square feet)	206	204	21
Industrial (1985 = 100)	96	90	85
What We Can Realistically Do			
Electricity consumption (QBtu)			
Building sector	19 3	21 7	24 5
Industrial sector	10 8	14 1	18 3
Energy intensity (all fuels)			
Residential (MBtu/household	180	148	140
Commercial (KBtu/square feet)	206	190	172
Industrial (1985 = 100)	93	83	76

Note [1] from Carlsmith et al, 1990

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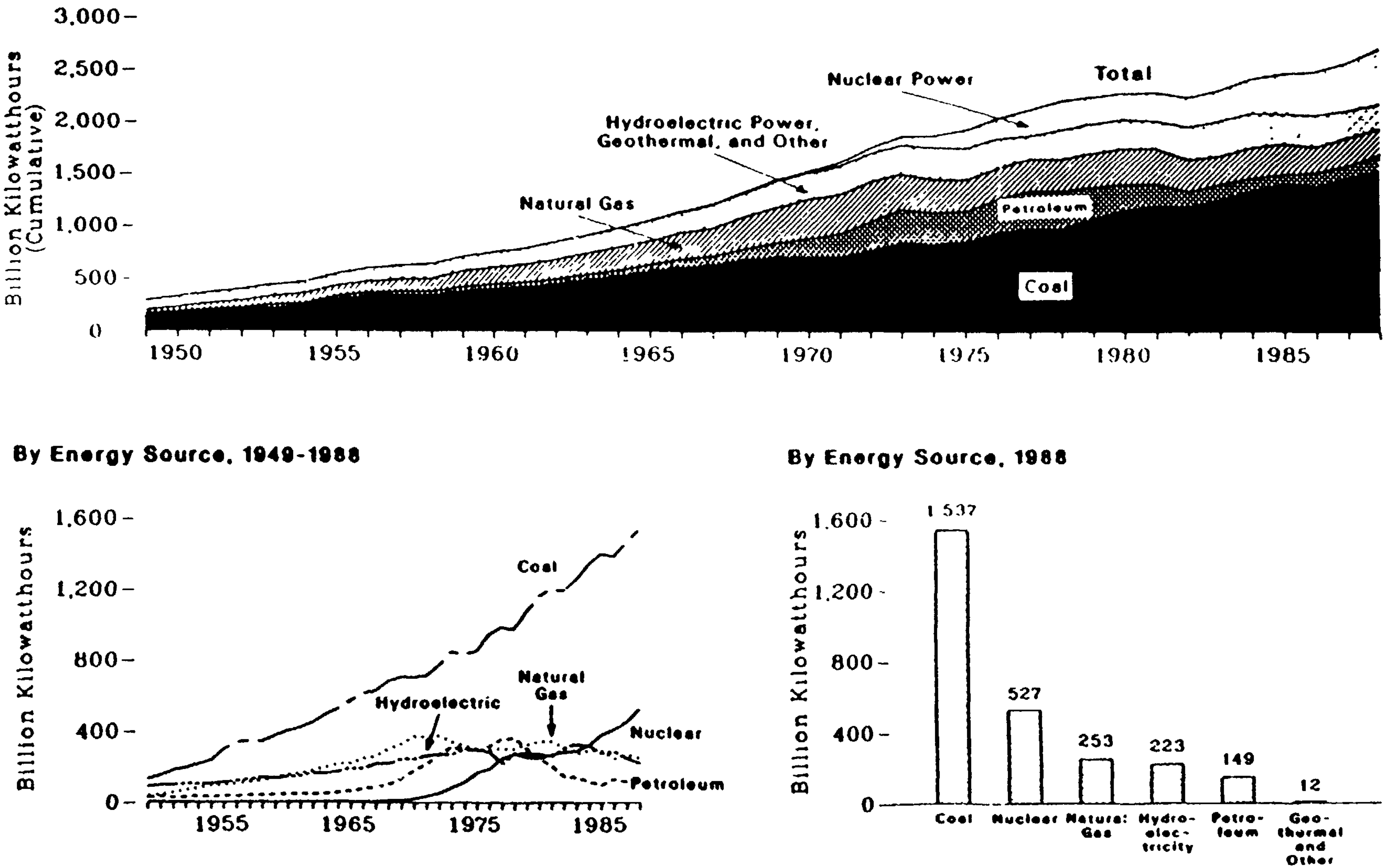
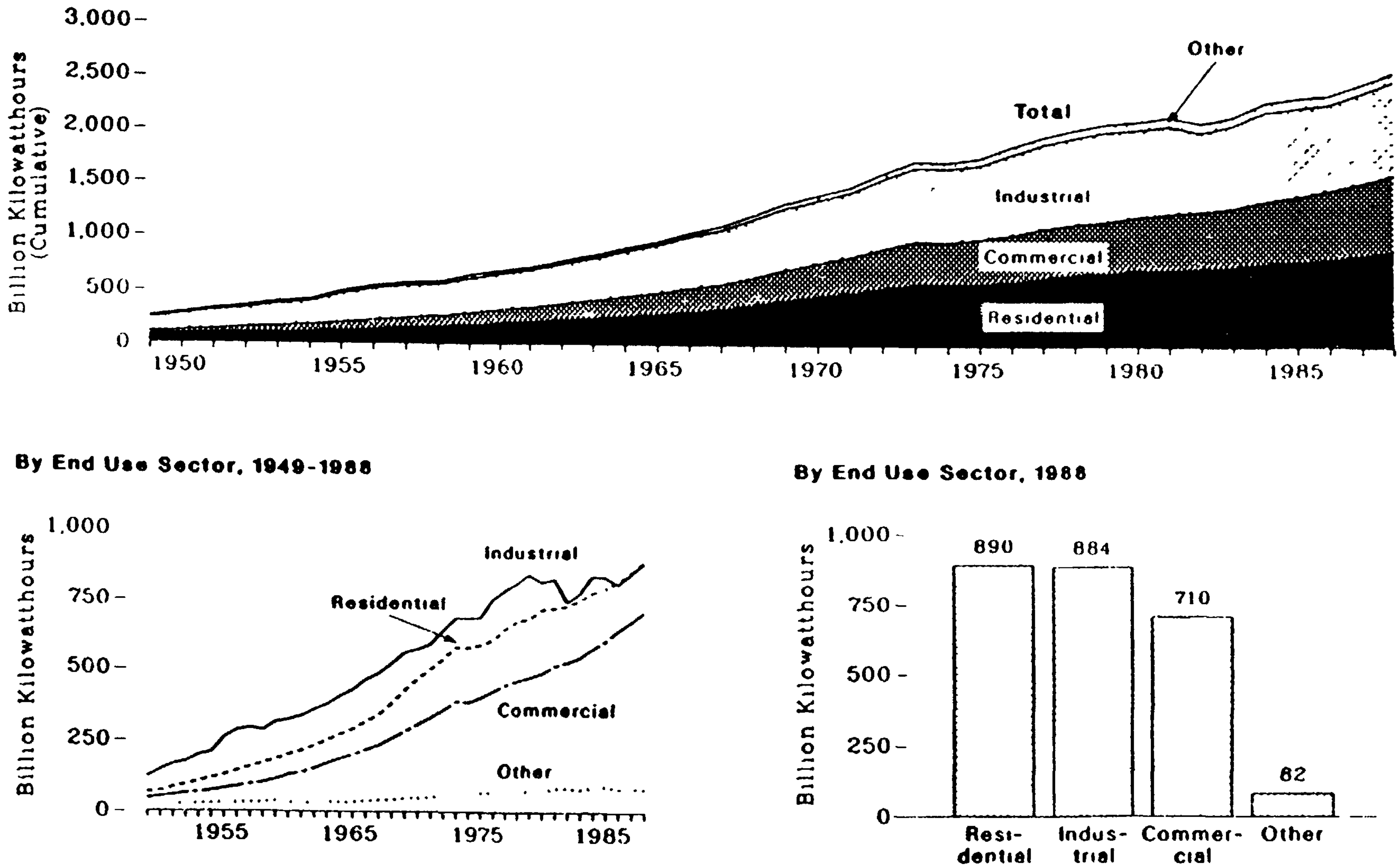
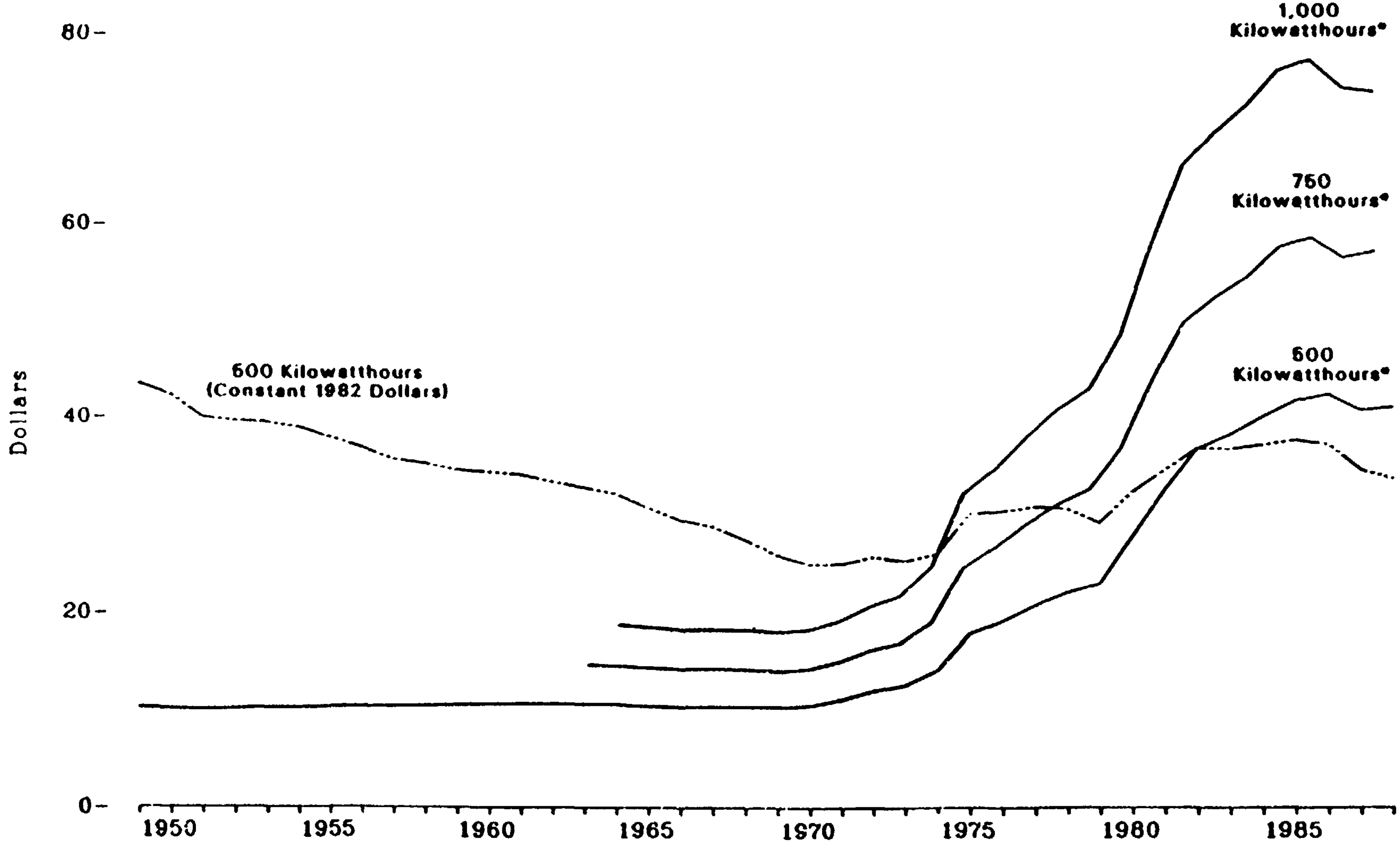


Fig. 1 Net Generation of Electricity by Electric Utilities by Energy Source, 1949-1988



Note 1949–1983 are "old series" data, 1984–1988 are "new series" data

Fig. 2 Electricity Sales by End-Use Sector, 1949-1988



*Current dollars.

Fig. 3 Residential Weighted Average Monthly Electric Bills, 1949-1988

Background Papers to

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GEOTHERMAL ENERGY: ITS ROLE IN THE GENERATION OF ELECTRICITY AND ITS ENVIRONMENTAL IMPACT

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ABSTRACT: Geothermal energy, as natural steam and hot water, has been exploited for decades to generate electricity and in district heating and industrial processes. The present geothermal electrical installed capacity in the world is 5,838 MW_e, and will reach 9,000 MW_e in 1995. Electricity is produced with an efficiency of 10-17%, and the cost of the kWh is competitive with conventional sources of energy. In developing countries where total installed electrical power is still low, geothermal energy can play a significant role: in El Salvador, for example, 19% of electricity comes from geothermal steam and 14% in the Philippines. Present technology makes it possible to control the environmental impact of geothermal exploitation. Geothermal energy can also be extracted from deep geopressured reservoirs in large sedimentary basins, hot dry rock systems and magma bodies. While the viability of hot dry rock technology has been proven, research and development are still necessary for the other two sources.

1. INTRODUCTION

Geothermal energy is the energy contained as **heat** in the Earth's interior.

The origin of this heat is linked with the internal nature of our planet and the physical processes occurring there. Despite the fact that this heat is in huge quantity and practically inexhaustible, even taking into account the Earth's crust alone and not the deeper areas of the planet, it is highly dispersed, seldom concentrated, and often at depths too great to be exploited industrially.

The Earth's heat moves toward the surface where it dissipates, but its effect is generally not much perceived; we are aware of its existence because of the higher temperature of rocks at increasing depths, showing that a geothermal gradient exists: it corresponds to 30°C/km, on the average.

There are, however, privileged areas on the Earth's crust accessible to our means where temperatures are well above the average values for those depths. This occurs when, a few km from the surface, there are magma bodies releasing heat. These heat sources are magma intrusions at depths of 7 to 15 km or, where the Earth's crust is thinner, the Earth's mantle itself.

The extraction and practical utilization of this large quantity of heat requires a carrier which transfers the heat toward the Earth's surface, up to accessible depths. This carrier is represented by geothermal fluids. These fluids are essentially rain water which has penetrated into the Earth's crust, heated up from contact with the hot rocks, and formed hot aquifers inside permeable formations. These aquifers, or reservoirs, are the geothermal fields. Where impermeable rocks cover the permeable formations, preventing or limiting the heat loss, steam may exist at high temperature (even 300°C) and pressure (Fig. 1).

If wells are drilled into the reservoir, hot fluids can be extracted and exploited. When geological conditions are particularly favourable, steam can be extracted and can be conveyed directly to turbines to drive alternators and produce electricity, in a way similar to conventional fossil-fueled plants. If a geothermal field produces hot water only, it can be exploited to generate electricity if the water temperature is above 85°C (by means of binary cycles, see below). If the temperature is lower than 85°C, the geothermal heat can be exploited in non-electrical uses, such as space heating and industrial processes, thus allowing the saving of higher quality energy.

Strictly speaking, geothermal energy is not a renewable source of energy. This statement comes from the fact that the natural replenishment by infiltration with rain water of a reservoir, under exploitation for decades by a large number of wells, will never occur, as experience shows. If the exploitation ceased, the full replenishment would probably take centuries. However, during exploitation, the reinjection of the used fluid back into the reservoir by means of reinjection wells can slow down the depletion of the field. This depletion is put into evidence by drops of pressures and outputs.

Hot areas of the Earth's crust where geothermal fields are to be found correspond to a belt of young volcanism, earthquakes and mountain-building, which runs on the margins of the continents. This belt is the well-known fire-belt of the Earth. It corresponds to the margins of major crustal plates, where melted rocks from the Earth's mantle come nearer to the surface. It is known that the basic concept of crustal plates and plate tectonics is that the rigid outer shell of the earth, the crust, is divided by a network of boundaries into separate blocks, which are the crustal plates. The plates comprise both the ocean floors and continental areas, and float and shift above the mantle. During their relative movement the plates may drift apart, forming fractures along their margins through which magmatic effusions rise. The plates may also collide, in which case their zones of collision are characterised by mountain-building areas, volcanic archipelagos, and the slipping of one plate beneath another. These geodynamic phenomena are responsible for the development of surface heat flow anomalies and geothermal fields.

2. THE GEOTHERMAL CONTRIBUTION TO THE GENERATION OF ELECTRICITY

Commercial generation of electricity from geothermal steam began in Larderello, Italy, in 1913, with an installed capacity of 250 kW_e. Since 1950, other countries have followed the Italian example. The 1990 status of worldwide geothermal development is shown in Table I, along with the figures for 1982, demonstrating that the installed electric capacity has doubled in the past eight years.

The world geothermal electric power at the end of 1990 was 5,838 MW [1]; by comparison, the world electric power from all sources was 2,556,036 MW in 1987 (this is the most recent available figure [2]). Geothermal energy thus continues to represent 0.2% of the world's electric power [3, 4].

Table I. Geothermal Electric Capacity in the World in 1982, 1990 and 1995.

	1982 (MW)	1990 (MW)	1995 (MW)
United States	936	2770	3200
Philippines	570	894	2164
Mexico	180	700	950
Italy	440	548	885
Japan	215	215	270
New Zealand	202	283	342
Indonesia	30	142	380
El Salvador	95	95	180
Costa Rica			110
Kenya	30	45	105
Iceland	41	45	110
Nicaragua	35	35	100
Turkey	0.5	20	40
China	4	21	50
USSR	11	11	70
France (Guadal.)		4	4
Portugal (Azores)	3	3	3
Guatemala		2	15
Greece		2	12
Romania		1.5	1.5
St. Lucia			10
Argentina		0.6	0.6
Thailand		0.3	3.3
Zambia		0.2	0.2
Total	2793	5838	9006

This figure shows that geothermal energy plays a very minor role on the world energy scene. However, if we distinguish between industrialised and developing countries, then the contribution of geothermal energy is clearly shown to be entirely different (Table II).

Table II. Percentage of Electric Capacity from Geothermal Energy on Total Electric Capacity for some Countries.

	Total electrical installed power (1987) (MW_e)[1]	Geothermal electrical installed power (1989) (MW_e)	% of the total power installed
Industrialized Countries			
USA	743,377	2212	0.3
Japan	176,419	215	0.1
Italy	56,403	548	1.0
New Zealand	7,434	167	2.2
Developing Countries			
El Salvador	500	95	19.0
Philippines	6,375	894	14.0
Nicaragua	395	35	8.9
Kenya	575	45	7.8
Mexico	26,788	700	2.6
Indonesia	10,430	142	1.4

[1] *United Nations (1989)*

2.1 Geothermal energy in the industrialised and developing countries

In the industrialised countries, where the installed electrical power reaches high figures (tens or even hundreds of thousands of MW_e), geothermal energy is unlikely, in the next decade, to account for more than one percent, at most, of the total.

In developing countries, however, with an as yet limited electrical consumption but good geothermal prospects, the electrical energy of geothermal origin could make quite a significant contribution to the total: at the moment, for instance, 14% of the electricity in the Philippines, 19% in El Salvador, and 8% in Kenya, come from geothermal sources.

The future contribution of geothermal energy to the generation of electricity in the world can be conservatively estimated at about 9,000 MW in 1995; 12,000 MW in the year 2000; 17,000 MW in 2010 and 25,000 MW in 2020 (5,838 MW in 1990).

2.2 Efficiency of generation

The efficiency of the generation of electricity from geothermal steam ranges between 10-17%, about three times lower than the efficiency of nuclear or fossil-fueled plants. This drop occurs because the geothermal steam has temperatures much lower than the steam from conventional boilers. Furthermore, geothermal steam has a chemical composition different from pure water vapour, because it generally contains non-condensible gases (CO_2, H_2S, NH_3, CH_4, N_2 and H_2) in variable quantities (1-50 g/kg of fluid) which represent a nuisance in the process of electricity generation.

2.3 Electricity generating cycles

The simplest and the cheapest of the geothermal cycles used to generate electricity is the direct non-condensing cycle. Steam from the geothermal well is simply passed through a turbine and exhausted to atmosphere: there are no condensers at the outlet of the turbine. Such machines consume about 15-25 kg of steam per kWh generated. Non-condensing machines must be used if the content of non-condensible gases in the steam is very high (greater than 50% in weight) and will usually be used in preference to the condensing cycles for gas contents exceeding about 10%, because of the high power which would be required to extract these gases from the condenser.

Condensing plants, with condensers at the outlet of the turbine and conventional cooling towers show a much lower consumption, only 6-10 kg of steam per kWh generated, but the gas content of the steam must be less than 10%, as previously said.

If the geothermal well produces hot water instead of steam, electricity can be generated, provided the water temperature is above 85°C, by means of binary cycle plants. These plants operate with a secondary, low-boiling point working fluid (freon, isobutane, ammonia, etc.). The working fluid is selected to optimize the power output from given geothermal well water and flow. The working fluid is vaporized by the geothermal heat through the vaporizer. The vapor expands as it passes through the organic vapor turbine which is coupled to the generator. The exhaust vapor is subsequently condensed in a water-cooled condenser or air cooler and is recycled to the vaporizer by the motive fluid cycle pump. The efficiency is still lower: between 2.8 and 5.5% [5]. However, the binary power plant technology has emerged as the most cost-effective and reliable way to convert large amounts of low temperature geothermal resources into electricity, and it is now well known that large low temperature reservoirs exist at accessible depths almost anywhere in the world.

2.4 Generation costs

In geothermal development for the generation of electricity, about 40% of total costs are related to the identification of the reservoir and to the drilling of production and reinjection wells, the latter to dispose of the spent fluids and to partially recharge the reservoir. Of the remainder, 50% goes to power plants and pipelines, and 10% to other activities.

2.5 Drilling wells

The cost (1990) of drilling ranges between US$ 800-1,200/m, and commercial well depth can reach 3 km. Drilling success is, on average, 50%. A good well with an output of 70,000 kg/h of steam with a gas content lower than 10%, assuming an average consumption of 7 kg of steam per kWh in a condensing plant, can support a 10,000 kW_e (10 MW_e) power station.

2.6 Power stations

Large geothermal power plants (100 MW_e) cost around US$ 1,000/kW, while the cost of small generating plants (2.5-10 MW_e) ranges between US$ 1,250-1,500/kW.

Plants with atmospheric exhaust (which exploit steam with high gas content) are cheaper than plants with condensers and cooling towers, but it was said that their steam consumption is higher: 15-25 kg/kWh compared to 6-10 kg/kWh from condensing cycles.

Binary plants, exploiting hot water, are more expensive, around US$ 1,500/kW (1.2 MW_e in size) [6]. This is because they are technologically more sophisticated, due to the fact that the working fluids used (freon, isobutane, etc.) are volatile, sometimes toxic, often flammable, and their emissions into the environment must be avoided.

2.7 The cost of the geothermal kWh

Compared with oil, geothermal energy remains attractive even if the price of crude is at US$ 10 per barrel [7, 8]. While the cost of electricity from oil with oil prices at US$ 10/bbl may be the same as from geothermal energy (including the cost of field research to locate the reservoir, of the wells and of the power plant), the advantage for some countries in using geothermal lies in the fact that the hard currency needed for oil import can be saved because the indigenous resource is utilized instead.

Estimated costs of the geothermal kWh are at present in the range of 4-6 US cents per kWh generated (every cost included). This range takes into account different geological situations, quality of steam, output of wells, size of power plants, etc.. A comparison of the cost of the kWh from different sources is given in Table III.

Table III. Estimated Cost, in US cents per kW·h for different sources (1986 dollars) [8].

		Outlook for 2000
Oil	4-8	
Coal	5-8	
Nuclear	5-16	
Small hydro	7	
Hydrothermal (geothermal steam)	4-6	
Geopressured (geothermal steam)	10	
Hot dry rocks	17	7
Magma (experimental)	20	
Wind	12	4
Photovoltaics	24	6
Solar thermal	12	4

3. THE ENVIRONMENTAL IMPACT OF GEOTHERMAL ENERGY

Utilization of geothermal heat requires the extraction of large volumes of steam or steam and water from the reservoir (for example, 15,000 t/h at The Geysers field in California, installed electrical capacity 2,000 MW_e, and 3,000 t/h at Larderello, Italy, installed capacity 400 MW_e).

Geothermal fluids have a chemical content which is site-specific, highly dependent on the rocks of the reservoir. The major environmental impact of geothermal exploitation is the pollution of air (exhaust of the spent steam into the atmosphere) and of water bodies (rivers and lakes), with the discharge of condensated steam from condensing plants, if reinjection wells are not used.

However, other forms of impact exist. Altogether, the main environmental concern comes from:

- air pollution;
- water pollution;
- land subsidence;
- induced seismicity;
- land use;
- noise;
- solid waste.

3.1 Air pollution

Steam from major geothermal fields has a content of non-condensible gases (CO_2, H_2S, NH_3, CH_4, N_2 and H_2) ranging from 1.5 to 53 g/kg of steam.

- Carbon dioxide is the major component, but its emission into the atmosphere (1.3-380 g/kWh) is well below the figures for natural gas, oil or coal-fired power stations per kWh generated (Fig.2).

- Hydrogen sulfide is the air pollutant of major concern in geothermal development. Its emissions, without any abatement, generally range between 0.3 and 9.6 g/kWh (Fig.3). H_2S is oxidated to sulfur dioxide and then to sulfuric acid and may cause acid rain. Without abatement, the specific emissions of sulfur from geothermal power plants can be comparable to those from coal-fired plants [9]. The California Ambient Air Quality Standard limits the H_2S level at 30 parts per billion (ppb) by volume at ground level. The odor threshold in air is about 5 ppb. In New Zealand, the hydrogen sulfide limit in geothermal areas is, instead, 5,000 ppb [10].

- Mercury concentrates with great preference (50-90%) into steam rather than into hot water, and the steam concentration ranges between 45-900 $\mu g/kWh$. With good dispersal into the atmosphere, by injecting the waste gases into the cooling tower plume, mercury concentrations in the immediate vicinity of a power station would be 0.01-0.1 $\mu g/m^3$ [11]. These levels are unlikely to present a health hazard, although Schroeder [12] considered that prolonged exposure to atmospheric levels of mercury in excess of 0.1 $\mu g/m^3$ may be harmful. However, the adopted maximum level for 8-hour industrial exposure is 50 $\mu g/m^3$ [13]. On a per kWh basis, emissions of mercury from geothermal power plants are comparable to the release of mercury from coal-fired power plants [14].

- Ammonia is emitted in the exhaust gas stream (57-1938 mg/kWh) but is rapidly diffused by atmospheric processes, and the values reach acceptable values very quickly.

- Radon-222, generally contained in the steam, is released into the atmosphere with the condenser vent-gas. Its content ranges between 10 and 2,054 nCi/kWh (in SI units, where $1Ci=3.7x10^{10}$ Bq, between 3700-78000 Bq/kWh). The levels of radon measured in the ambient air outside the geothermal plants at The Geysers (California) are in the range of 30-150 pCi/m^3, and at Larderello (Italy) 150 pCi/m^3, well below the average for air over continental land areas, which is about 300 pCi/m^3; this last figure represents the international limit in ambient air in uncontrolled areas [15, 9].

3.2 Water pollution

The pollution of rivers and lakes may also be associated with power production and management of spent geothermal fluids if they are not reinjected into the reservoir. In natural steam reservoirs, most of the pollutants are found in the vapour state, as described, and the pollution of superficial water bodies (rivers and lakes) is more easily controlled than in the exploitation of geothermal water reservoirs.

In hot water reservoirs, water and steam (if present) must be separated at the surface (the steam is used for the generation of electricity), and the volume of water to be disposed of (which may contain high quantities of salts, even above 300 g/kg of extracted fluid) can range up to 70 kg/kWh, more than four times the steam supply. In addition, waste steam condensate must be added to the waste water (20% of steam supply, the remainder is discharged into the atmosphere through the cooling towers).

The water and the condensate generally carry a variety of toxic chemicals in suspension and solution: *arsenic*, *mercury*, *lead*, *zinc*, *boron*, *sulfur*, together with large amounts of *carbonates*, *silica*, *sulfates* and *chlorides*.

Reinjection into the geothermal reservoir is the most common method of disposal. In addition, reinjection may also help to maintain reservoir pressure, to extract additional heat from the rock, and to prolong the useful life of the resource.

3.3 Land subsidence

The weight of the rocks above a reservoir of groundwater, oil or geothermal fluids is carried in part by the mineral skeleton of the reservoir rock, and in part by fluids in the rock pores. As fluids are removed, pore pressure is reduced, and the ground tends to subside. Less subsidence is expected with harder reservoir rock.

The scale of geothermal fluid extraction is comparable to large agricultural groundwater withdrawals. A serious potential for subsidence is associated with geothermal development.

Water-dominated fields subside more than steam-dominated fields. As an example, the Wairakei water-dominated geothermal field in New Zealand (150 MW_e) subsided 4.5 m between 1964 and 1974, with the extraction of 622 Mtons of fluid. The Geysers steam-dominated field (2,000 MW) subsided 0.14 m between 1973 and 1977 [10].

Subsidence can be controlled or prevented by the reinjection of spent fluids. Renjection could, however, induce seismicity.

3.4 Induced seismicity

Many geothermal reservoirs are located in regions with high frequency of naturally occurring seismic events.

Water reinjection into the reservoirs may induce seismic activity by reducing rock stress, loosening tight vertical faults, and causing the release of tectonic stress accumulated along them.

The correlation between seismicity and water reinjected in the wells located in a geothermal area (Larderello, Italy) suggests that a percentage of low-magnitude events are induced. However, the data indicate that an increase in the quantity of injected water does not produce an increase in the maximum magnitude value.

3.5 Land use

Much of the land within geothermal field development remains usable even after full operational status is achieved.

Each 110 MW_e power plant at The Geysers (USA) requires 14-20 wells to provide the approx. 909,000 kg/h of required steam supply (average 50,000 kg/h per well) [10].

The amount of land actually disturbed at The Geysers (wells, pipelines and power plants) is 1,900-3,200 m^2/MW. Most wells are directionally drilled, a site $<$10,000 m^2 can accommodate 5 wells.

In Larderello, Italy, the area necessary to host a 20 MW_e geothermal power plant is ~10000 m^2, of which 1,000 m^2 are covered [15].

3.6 Noise

Wells, newly drilled or during maintenance, have a noise level of 90-122 dB at free discharge, and 75-90 dB through silencers. The pain threshold is 120 dB at 2,000-4,000 Hz. By comparison, a jet takeoff is 125 dB at 60m [10].

3.7 Solid waste

A 50 MW_e geothermal power plant may produce 24,000 kg/day of silica, to be handled and disposed of as hazardous solid waste because of Pb, Zn, etc.

The cooling tower sludge is particularly hazardous because it very often contains As and Hg.

4. EXPLOITATION OF GEOTHERMAL ENERGY IN THE FUTURE FOR GENERATION OF ELECTRICITY: FROM GEOPRESSURED RESERVOIRS, HOT DRY ROCK SYSTEMS AND MAGMA BODIES

4.1 Geopressured reservoirs

These are deep reservoirs (4-6 km) in large sedimentary basins containing pressurized hot water which had remained trapped at the time of the deposition of the sediment, and at pressures of up to 100% in excess of the hydrostatic pressure corresponding to that depth.

Geopressured fields could produce not only the thermal energy of the pressurized hot water, but also hydraulic energy, by virtue of the very high pressure, and methane. The US Dept. of Energy has sponsored a series of geoscience studies to resolve key uncertainties in the performance of geopressured reservoirs [8].

The program presently has 3 geopressured geothermal wells in Texas and Louisiana, and one of the wells has a 1 MW_e hybrid power system converting some gas and the thermal energy into electricity [16]. However, research has to confirm the economic feasibility and long-term use of this resource.

4.2 Hot Dry Rock systems

HDR geothermal reservoirs differ significantly from conventional geothermal reservoirs, which probably exist only in geologically favored regions of the world. In these regions, nature provides not only the hot rock, but also hot water or steam which is easily extracted for the generation of electricity.

HDR reservoirs are, instead, man-made reservoirs in rocks artificially fractured, and thus any convenient volume of hot dry rock in the earth's crust, at accessible depth, can become an artificial reservoir.

A pair of wells is drilled into the rocks, terminating some hundred meters apart. Water is circulated down the injection well, through the HDR reservoir, and then returns to the surface through the production well, and thus transfers the heat to the surface as steam or hot water (Fig.4).

In the US, at Los Alamos, New Mexico, an HDR project has been a successful pioneering effort, now brought to the threshold of economic viability [8]. In Cornwall, the UK has an on-going research program established in 1976 [17], and in Alsace a French and German cooperation supported by the EEC has been active since 1987 [18].

However difficulties still remain in creating a large heat exchanger at depths of several kilometres, possessing a large heat exchange area and volume, uniformly swept by the circulating water, but having a reasonably low hydraulic resistance [19].

4.3 Magma bodies

Thermal energy contained in magmatic systems represents a huge potential resource. The goal of the US Magma Energy Extraction Program is to determine the engineering feasibility of locating, accessing, and utilizing magma as a viable energy resource.

The first objective of the Program is to develop technology that would enable magma-generated power to be produced in the cost range of US cents 10 to 20/kWh by the year 2000.

The realization of this objective will require progress in four critical areas. These are 1) magma location and definition: crustal magma bodies must be located and defined in enough detail to position the drilling rig; 2) drilling: high temperature drilling and completion technology require development for entry into magma; 3) materials: engineering materials need to be selected and tested for compatibility with the magmatic environment; 4) energy extraction: heat extraction technology needs to be developed to produce energy extraction rates sufficient to justify the cost of drilling wells into the magma [20].

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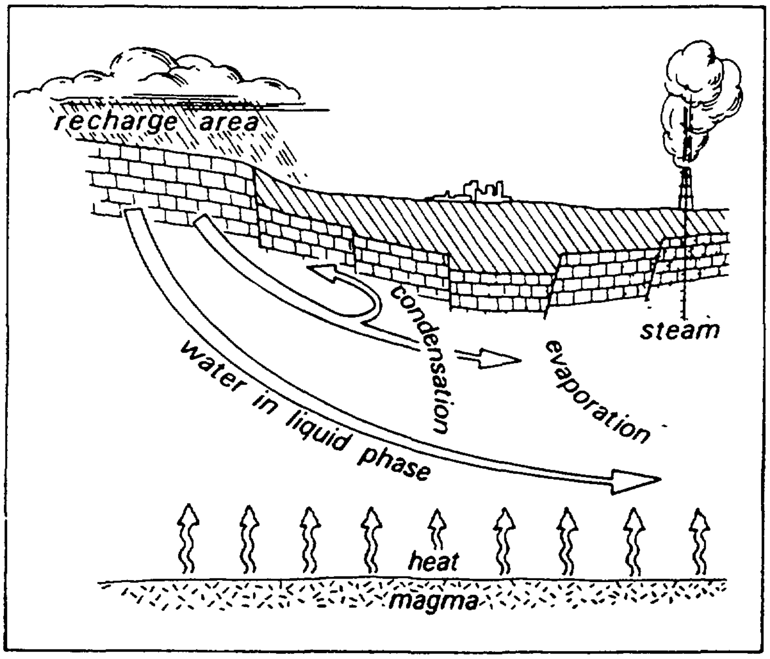

Fig.1 Schematic representation of a geothermal field.

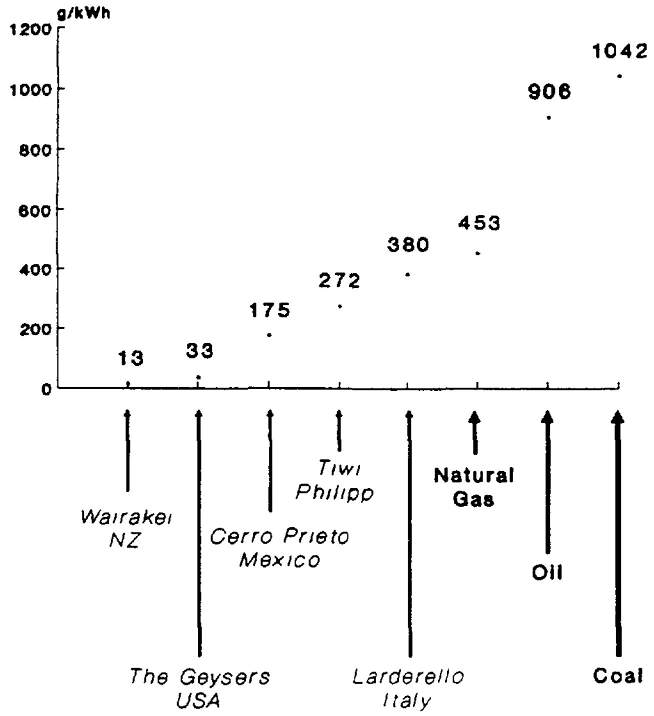

Fig.2 Comparison of carbon dioxide emissions from geothermal and fossil fuel-fired power stations.

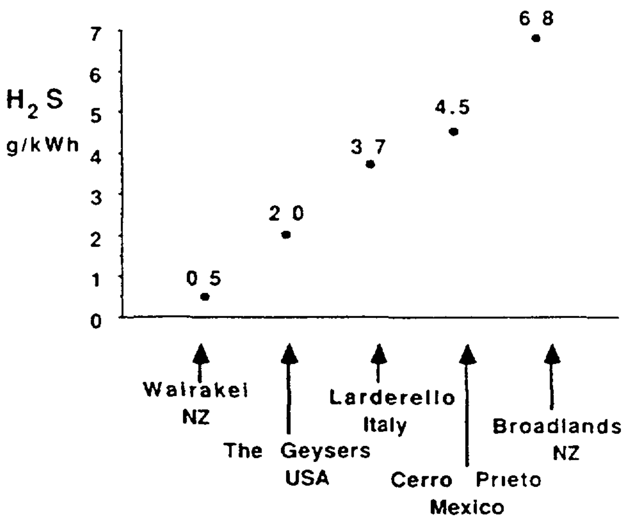

Fig.3 Hydrogen sulphide emissions from geothermal power stations.

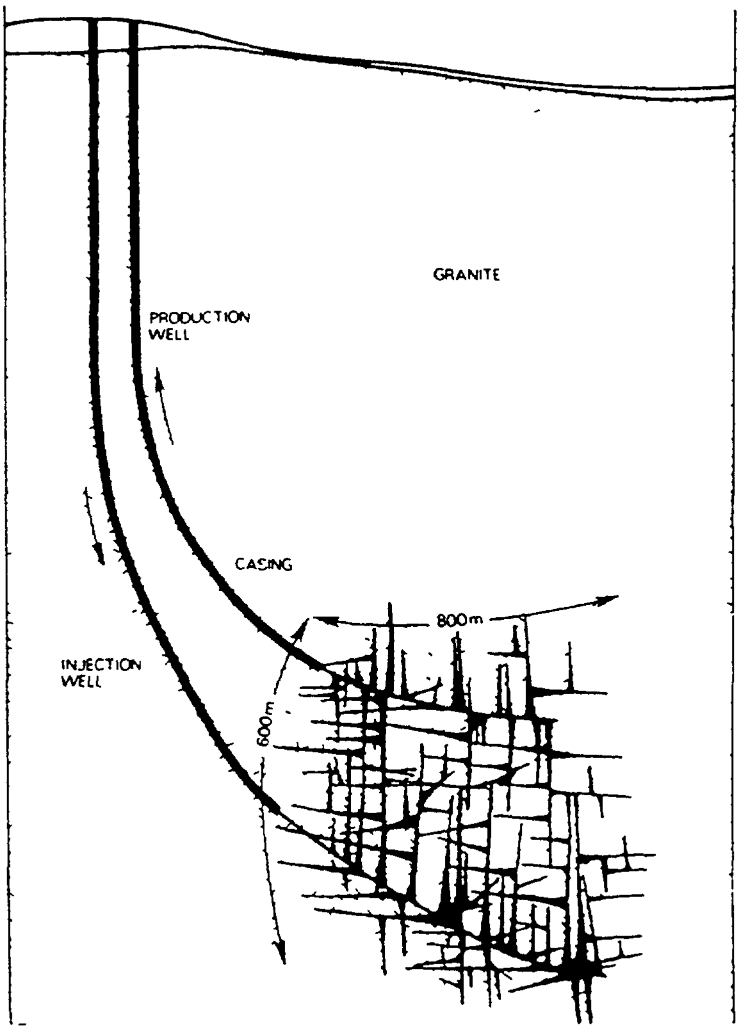

Fig.4 Schematic representation of a Hot Dry Rock reservoir formed by artificial fracturing.

WIND ENERGY SYSTEMS:
RESOURCES, ENVIRONMENTAL ASPECTS AND COSTS

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ABSTRACT: Wind is generated by atmospheric pressure differences in the atmosphere, driven by solar power. Of the total 173,000 TW of solar power reaching the earth about 1,200 TW (0.7%) is used to drive the atmospheric pressure system. Only a small portion of the wind's energy can be converted into electricity by means of wind turbines. Because of the economical, physical planning and environmental reasons, the total maximum world potential is about 1 TWyr/yr, which is roughly equal to the present world electricity demand. At present, the total installed wind capacity is increasing rapidly. The present growth rate is about 370 MW/yr.

This paper addresses in detail the actual conversion process of the kinetic energy of the wind into electricity, the distribution of the wind resources over the world and the restraints in exploiting the resources. The latter comprise physical and institutional constraints, effects on birds, acoustic noise, visual impacts, public acceptance, etc. Also the aspects of integrating wind turbine systems into national electricity supply grids is discussed. The environmental impact of wind energy is addressed in terms od avoided emissions. Finally, the economic aspects, both generating cost and the total cost are addressed.

[1] The author wishes to thank the European Wind Energy Association (EWEA) for permitting the use of material from the EWEA Strategy Paper and Erik Lysen of Lysen Energy Consultants, co-author of the EWEA Strategy Paper.

1. INTRODUCTION

Each energy resource has its restraints, and wind power is no exception. One cannot install wind turbines too close to cities, turbines may produce too much noise, they may effect birds, they are judged to be ugly by some (and beautiful by others), there may be legislation requiring long procedures for building permits. The paper addresses these planning aspects.

Costs of wind energy is a crucial subject in the discussions on the potential contribution of this renewable source. The paper addresses the investment and generation cost taking into account the dependency of the energy output of the varying wind regime. Further the 'value' of wind energy will be assessed in terms of the avoided fuel and environmental cost.

The emphasis of the paper is on grid connected machines, but there is also attention to wind energy applications for remote and rural areas, e.g. in developing countries.

For a description of the market aspects of wind energy reference is made to a paper which was produced for the European Wind Energy Association by Musgrove and Lindley [42]. Further the paper describing the development of large wind turbines, presented at the Euroforum New Energies Congress in Saarbrücken by J. Schmid and H. Beurskens, is considered relevant in this respect [38].

In writing this review the author was able to use the results of the Strategy Paper and attached background documents published in the beginning of 1991 by the European Wind Energy Association (EWEA). These papers contain valuable material which has partly been reproduced by permission of the EWEA [42, 43].

2. WIND POTENTIAL

2.1 World resource

Wind is generated by atmospheric pressure differences in the atmosphere, driven by solar power. Of the total 173,000 TW of solar power reaching the earth, about 1,200 TW (0.7%) is used to drive the atmospheric pressure system. This power generates a kinetic energy reservoir of 750 EJ with a turnover time of 7.4 days [1]. This conversion process mainly takes place in the upper layers of the atmosphere, at around 12 km height (where the 'jet streams' occur). If we assume that about 1% of the kinetic power is available in the lowest strata of the atmosphere, the world wind potential is of the order of 10 TW.

In 1981 IIASA has estimated the worldwide technical wind potential at 3 TWyr/yr, with a limitation to continental areas with 1,000 km coast line between 50° Northern and Southern latitude [2]. Because of economical, aesthetical and physical planning limitations roughly 1/3 of this potential could be realized, or nearly 1 TWyr/yr. The total commercial energy use of the world in 1988 was 11 TWyr/yr of thermal power [3]. The average world electrical energy demand was around 1 TWyr/yr.

One concludes that, purely on a theoretical basis, and disregarding the mismatch between supply and demand, the wind could supply an amount of electrical energy equal to the present world electricity demand.

A study conducted by the World Meteorological Organization paints a more detailed picture of the geographical distribution of available wind resources around the world. The analysis has been based on wind measurements taken by meteorological institutes [34]. Figure 1, taken from this study, shows the world wind energy map.

Mean wind speeds - at the standard measuring height of 10 m - vary from below 4 m/s in Central Asia and Africa, to over 6 m/s along the coastal regions of Northern Europe and America.

As a consequence of the non-linear relationship between wind speed and the power (and hence the energy) of the wind one should be careful in using average wind speed data (m/s) to derive wind power data (W/m^2). Local geographical circumstances may lead to meso scale wind structures which have a much higher energy content than one would calculate from the most commonly used wind speed frequency distribution Rayleigh). As a consequence of the variability of the wind speed the annual energy is roughly double of that based on the assumption of a constant wind speed equal to the average wind speed. Making allowances for the increase of wind speed with height, it follows that the energy available at, say 25 m varies from around 1.2 MWh/m^2/year to around 5 MWh/m^2/year in the windiest regions. Higher energy levels are possible if hilly sites are used, or if local topography funnels a prevailing wind through valleys.

Numerous regional and even local wind atlases have been produced since the publication of the WMO note. The most detailed data are available in the United States of America and in the countries of the European Communities [8]. An example is given in Fig. 2. States like California and countries like Denmark, the Netherlands and Switzerland have detailed atlases and handbooks which also allow the determination of local effects like terrain roughness, complex terrain and obstacles on the undisturbed average wind speed.

2.2 Wind turbines

The theoretical maximum aerodynamic conversion efficiency of wind turbines - from wind to mechanical power - is 16/27. However, the fundamental properties of even the most efficient of modern aerofoil sections - used for blades of large and medium size wind turbines - limit the peak achievable efficiency to around 45%. In practice the need to economize on blade costs tends to lead to the construction of slender bladed, fast running wind turbines with peak efficiencies a little below the optimum, say 42%. The average, year around efficiency of most turbines is about half this figure. This is due to the need to shut down in low or high winds, to limit the power once the rated level is reached. Further a reduction of average efficiency is caused by generator and gearbox losses and by the fact that the machine does not always operate in its optimum working point.

2.3 Potential studies, the case of Europe

Apparently the real usable wind energy potential is not determined by the prevailing wind speeds alone, but by other limiting factors as well. These factors are:

- the availability of sites (the number of sites is restricted by environmental constraints such as possible effects on birds' life, acoustic noise emission, electro-magnetic interference, physical planning regulations, land use, land ownership; see chapter 3)

- grid integration constraints (voltage and frequency instabilities, etc.)
  To illustrate how these constraints effect the wind energy potential we will quote some results from European studies.

In Denmark a total wind potential of 8.2 GWyr/yr on land was estimated. Conflicting interests reduced this figure to about 2.6 GWyr/yr. It was concluded that the resource was large compared to amount which could actually be absorbed by the grid: 0.45 GWyr/yr. For the offshore areas with water depths between 6 and 10 m, a total contribution of 0.57 GWyr/yr was estimated, after realistic deductions for constraints [9].

For the Netherlands the total on-shore wind potential has been estimated to vary between 3,500 MW (severe environmental constraints) to 8,700 MW (flexible constraints) installed power, with outputs between 0.8 and 1.9 GWyr/yr [10]. The offshore potential has been estimated at 7,000 MW (1.4 GWyr/yr), after deductions for shipping lanes, oil exploration, etc.. SEP studies [7] indicate that 1,000 to 1,600 MW of wind capacity can be absorbed by the national grid with few losses. The total installed capacity in electricity plants is about 14,000 MW.

For the United Kingdom two studies (CEC and UKDOE) yielded a similar result: about 9,000 MW could be absorbed in the grid, without operational penalties (2.1 GWyr/yr) [9]. The UK off-shore resource was estimated at no less than 25.1 GWyr/yr, comparable with the total UK electricity production of 227.4 GWyr/yr at present. It was concluded that the offshore resource would not be a limiting factor in the development of off-shore wind energy in the UK.

A recent paper by Grubb [11] concluded that a technical potential of no less than 114 Gwyr/yr (at 30 m) is available on-shore. Site limitations would reduce this to 13.7 GWyr/yr in the optimistic and to 0.9 GWyr/yr in the pessimistic case. He concludes that a potential of 4.6-11.4 GWyr/yr on-shore is possible, which is 15% to 35% of the present demand.

A CEC study [4] indicated how the wind energy resources are distributed within the European Community, see Fig. 3.

From the studies and estimates mentioned above it can be concluded that for the EC as a whole the wind potential is larger than the electricity demand, which has increased from 138.6 GWyr/yr in 1980 to about 177 GWyr/yr in 1989 [30]. For individual countries (Belgium, Luxembourg and the FR Germany) the wind potential is smaller than the national electricity demand.

Planning, environmental and integration restrictions reduce the exploitable wind power (according to present thinking) to about 10% of the demand. E.g. if the electricity demand in a sustainable European Community would level off at 230 GWyr/yr, this implies an exploitable wind potential of 23 GWyr/yr, to be generated with a wind capacity of the order of 100,000 MW. The development of suitable conversion and storage systems may further increase this potential.

2.4 Achievements

The world market for wind turbines of all types and sizes grew from just 34 MW in 1981 to 567 MW in 1985. Most of the growth was generated by the Californian windfarm market, which itself was created by a combination of US Federal and Californian State legislation that provided financial incentives to investors.

The expiration of the USA energy tax credits at the end of 1985 was the single most important factor reducing world demand to 339 MW in 1986. Figure 4, taken from [44], shows the growth of the world market for all sizes of turbines and clearly demonstrates how sales have been dominated by the North American windfarm market. The same figure shows however that sales in Europe over the same period have increased. The data from and including 1988 onwards represents a projection by the author Jaras following his own market study. The estimates are based on announced national programmes, industry market research and reviews of the literature. They assume that:

- the North American market will continue at 200 MW annually until 1991;
- the European market will grow to 100 MW annually by 1990. This assumption was based on announced programmes and legislation in Denmark, the Netherlands, Germany, Italy and the United Kingdom and the European Commission's so-called 'Valoren' subsidy programme for windfarms to be built in the Republic of Ireland, Spain, Portugal, Italy and Greece.
- all other markets will gradually grow to 70 MW annually by 1991. This assumption is largely supported by activities and government supported programmes already underway in China, India, Soviet Union and Israel.
- oil prices remain steady.

The growth of the market to date has resulted in the installation of approximately 20,000 grid connected turbines which in 1989 generated approximately 2.2 billion kWh. Much of this growth has taken place in California with a total installed power and generation in 1989 amounting to 1,335 MW and 2.1 billion kWh respectively. Overall Jaras projects that the market will gradually increase from about 300 MW a year to almost 400 MW by 1991, with about 50% of the market being outside California.

3. PLANNING CONSTRAINTS

3.1 Physical or institutional restrictions

In wind potential studies such as for the Norweb area in the UK [12] the reduction of the available wind potential by planning restrictions of different nature is carried out on a one square kilometer basis.

In each square kilometer physical constraints were identified, such as cities, towns, villages, lakes and woodlands, and institutional constraints such as National Parks and Green Belts. Using an existing land classification system the number of turbines which could be sited in each square was then calculated on the basis of minimum allowable distances between the turbines and minor roads. The effect of these restrictions was considerable: from a potential of 1.37 GWyr/yr down to 0.4 GWyr/yr or to 29%.

In the study for the Netherlands [10, 13 (ch.2)] squares of 5 by 5 km were used, within which the areas where wind turbines could be located are determined. The process is indicated in Fig. 5. Here the combined effect of applying the different restrictions is also considerable: from 8,700 MW down to 3,500 MW, or to 40%. The individual effect of the different restrictions on the wind potential in the Netherlands are indicated in Figs. 5 and 6, which clearly illustrates that 'nature' (including damage to birds) and 'landscape' are most pronounced.

3.2 Birds

The potential damage to birds is described in [13]:

- bird victims can be the result of collisions against tower or blades,
- breeding or resting birds can be disturbed in the turbine vicinity.

Research is taking place, amongst others, at the Research Institute for Nature Management (RIN) in the Netherlands and the Game Biology Station in Denmark. In a long-term study by RIN on the effects of the 7.5 MW wind plant (a row of 25 turbines of 300 kW) in Urk, Netherlands, it was found that on the average 0.1 to 1.2 bird victim per day can be expected on this wind plant. It was concluded that the number of bird victims per kilometer of wind farm was up to ten times smaller than that of a km of high voltage transmission line, and comparable with a kilometer of motorway [14].

A report by Ornis Consult in Denmark (owned by Denmark's ornithologist association) states that, after observations of nine medium and small scale wind plants throughout Denmark, it was found that birds have not really been disturbed by wind turbines. Birds seem to get used to the machines and learn, as a matter of routine, to fly around them [15].

In the USA the bird issue has taken a different turn. The mass media have taken up the issue since it has been reported that one bald eagle, America's national symbol, has been killed. When reports mention that 90 raptores have been killed (Note: by 7,000 wind turbines over 9 years) people tended to translate this into 90 eagles [17].

3.3 Acoustic noise

The nuisance caused by turbine noise is one of the important limitations of siting wind turbines close to habituated areas. The nuisance level is determined by two factors [13]: (1) the acoustic emission of the turbine and (2) the acceptable immission level.

The acoustic emissions are composed of a mechanical and an aerodynamical component, which are a function of wind speed. Analysis shows that for most turbines with rotor diameters up to 20 m the mechanical component dominates, whereas for larger rotors the aerodynamical component is decisive. One of the IEA reports on Recommended Practices for Wind Turbine Testing and Evaluation has been devoted to the measurement of the noise emission from wind turbines [18]. An example of the acoustic emission of wind turbines as function of their rotor diameter is presented in Fig. 7.

The acceptable immission level strongly depends on local regulations. An example of a strict regulation is the Dutch regulation for 'silent' areas, where a maximum immission level of 40 dB(A) near residences is allowed, at a wind speed of about 5-7 m/s. At this wind speed level the turbine noise is most distinctly audible [13].

When emission and immission levels are known then the minimum distance between wind turbines and residential areas can easily be calculated.

3.4 Visual impact

The visual impact of the turbines, although of a rather subjective nature, is a realistic planning restriction, particularly for areas of (in the UK jargon) Outstanding Natural Beauty. It should be noted, though, that the element of 'getting used to' the turbines is quite important here. The Danish and Dutch classical windmills were quite distorting elements in the landscape when first erected; now they are a first class tourist attraction.

In a recent study by the University of Leiden it was found that the public appreciation of a landscape is less the more wind turbines are installed [22]. In the study 110 persons were interviewed using photos without and with wind turbines. The size of the turbine has much less effect than their number, so the team concludes that it is best to install large (1 MW size) machines. The respondents had a preference for turbines in lines, particularly along roads and canals. The coherence and clarity of the landscape apparently plays an important role. It was also found that the effect of installing turbines in an industrial area gave much less reduction of the appreciation than with for example half- open landscapes.

A special case of visual 'impact' is the effect of the shadow of the wind turbine, particularly of the rotor blades. Of course this only occurs in situations where the wind turbines are installed close to places where people live or work. The effect can easily be predicted beforehand by calculating the hourly position of the shadow for each month of the year.

3.5 Public and political acceptance

Wind power seems to enjoy a rather positive image as a pollution-free technology. The general tendency of the public is, however, to favour the installation of wind turbines at some distance from their own back yards (the NIMBY syndrome). An interesting result from a study on the attitude of people living close to a 1 MW wind turbine in the Netherlands was that their acceptance sharply <u>increased</u> after erection of the turbine [13]. Apparently the people had all kinds of ideas about the possible nuisance to be caused by the turbine, which turned out to be much less than expected when the turbine actually operated.

An enquiry carried out by the University of Amsterdam among persons living near wind farm projects revealed that the public acceptance before the actual realization of the project is considerably higher in cases the public is informed on the plans in advance of press releases and the appearance of news paper articles [36]. The so called NIMBY syndrome often was virtually absent especially in those cases when the people were involved in the planning process itself.

In Denmark, the Netherlands and the Federal Republic of Germany the national governments (and some provincial governments as well) have issued financial incentives for prospective buyers of wind turbines and/or manufacturers. Wind power has found a place in the official planning documents of the electric utilities. In the Netherlands, for example, the official target of 1,000 MW of wind capacity in the year 2000, figures in the national electricity planning, including the expected capacity credit of 165 MW, implying a reduction of the fossil fired plant capacity by this amount.

The UK government seems more reluctant towards wind power. although the country has the biggest wind potential in the EC.

3.6 Legislation

There are a large number of legislative obstacles and regulations which restrict or slow down the installation of wind turbines (other than the restrictions mentioned already) [19]:

- legislation (or lack of it) concerned with obtaining planning or building consent to construct wind turbines,
- regulations concerned with the need for insurance for third party or other risks,
- regulations controlling the connection of wind turbines to a grid,
- legislation concerned with taxation or 'rating' of wind turbines that unfavourably penalizes turbines vis-a-vis conventional sources of electricity,
- government subsidies for conventional sources, which effectively subsidize generation costs,
- the nonrecognition of social costs of conventional sources,
- the absence of a legislative framework which allows private generation, or obliges the utilities to invest in windpower.

Legislation and regulations in the EC member states have been reviewed by Didier and Associates [20].

3.7 Telecommunication interference

Wind turbines present an obstacle for incident electromagnetic waves, which will be reflected, scattered and diffracted. This means that wind turbines may interfere with telecommunication links. The IEA has provided preparatory information on this subject, identifying the relevant wind turbine parameters (diameter, number and cross-section of blades, speed, etc.) and the relevant parameters of the potential vulnerable radio services (spatial positions transmitter and receiver, carrier frequency, polarization, etc.) [23].

It is clear that wind turbines should not interfere with telecommunication links, nor should they interfere with residential radio and TV reception. The paths of for example microwave links are well-known, and simply have to be avoided. For wind turbines close to residential areas it has been shown that TV reception can be influenced. In some cases wind turbines had to be stopped in the evening hours in order to permit people to watch TV broadcasts.

3.8 Safety

Accidents with wind turbines are rare, but they do happen, as they do happen in any other industrial activity. The insurance companies in the USA, with most of the experience with large numbers of wind turbines, agree that the wind industry has a relatively good safety profile.

Lethal accidents have happened in the USA as well as in Europe. Virtually all accidents should not have happened from an operation point of view [24].

Blade throw also rarely occurs, and if it happens it is mostly under extreme circumstances. A detailed analysis of blade throw is given by Turner (Chapter 13 of [13]). He concludes that, with a probability of failure of 10^{-5}, the probability of a person being hit is 10^{-7} near the tower and 10^{-10} at 600 m distance.

Discussing in great detail the probability that people, who find themselves in the vicinity of wind turbines, are fatally hit by thrown components, is considered useless. In general the level of accepting risks caused by failing technical installations in daily life varies very much with the personal involvement of an individual. We tend to accept a much higher chance of being injured by a car accident than of being effected by the results of an accident with a nuclear plant.

The definition what is safe and what is unsafe is a rather arbitrary one. The Dutch law, for instance, uses a system where the product of the effect and probability of occurrence of an event determines the safety level (Fig. 8). This however does not guarantee that the general public also perceives the concerned technology being safe when it is in the lower triangle of Fig. 8. The debates about the applications of nuclear energy is a typical illustration. An illustration of the opposite is the fact that the general public does not complain about the risks connected to the system of private transport. A brief analysis shows that wind turbines are 'safe' for people in the surroundings, even if a component is thrown several times a year and people are in the vicinity of the wind turbines all the time.

The conclusion thus is that avoiding catastrophic failures of the wind turbines is the most effective way of increasing the public acceptance of wind turbines from the point of view of safety.

This implies:

- there is no need for further analyses of the chance of injuring people after blade throw or other failures.

- there is an urgent need for an analysis of the reliability of wind turbine (components).

A good insight can be obtained by reliability analysis by means of fault tree analysis and reliability assessment methods carried out on the most representative existing machines.

In 1987 an EC project was initiated to draft a conceptual European safety standard for wind turbines. The document addresses the safety philosophy, structural integrity, personnel safety, loads and load cases. The aim of the document is to give guidance to the designers in order to conceive a wind turbine in such a way that the probability of catastrophic failures of the wind turbine is at an acceptable level. The basis of this document was laid by the Dutch, Danish and German standards. The production of this document was facilitated by the publication no. 6 of the IEA Recommended Practices [25].

The International Electrical Committee (IEC) has taken the initiative to produce an international official standard on safety. A review of the international developments in this field is given in [37].

4. GRID INTEGRATION

A wind power plant which operates in parallel to an electricity grid can statistically be treated in just the same manner as any other power plant. For each power plant one can calculate the chance that the plant (or a part of the plant) cannot supply the expected load and that the other plants in the network have to take over. Because of the variability of the wind an installed MW of wind power has a lower statistical availability than a MW of a conventional plant. Any MW of wind added to the system, however, increases the reliability of the system as a whole. Now the so called 'capacity credit' of wind is defined as the amount with which the conventional capacity can be decreased to arrive at the same reliability (or better: Loss-of-Load-Probability) as in the situation without wind turbines.

By statistical analysis it can be shown that to first order any item of power plant added to a power system provides additional firm capacity equal to its average power, provided it represents a small part of the total system. This is a general rule which also applies to wind turbines [16]. The more wind turbines are connected to the network, the lower the capacity credit becomes.

For example, in the Dutch situation the capacity credit of 1,000 MW of wind capacity is 165 MW. In other words: when 1,000 MW of wind capacity is available, then 165 MW less conventional capacity needs to be installed. The capacity credit is higher the more stable the wind regime is (cf. in trade wind areas) and the more unreliable the plants in the network are. For the Netherlands the capacity credit as a function of the wind capacity is shown in Fig. 9.

5. ENVIRONMENTAL ASPECTS

5.1 Energy costs of materials

Energy analysis of wind turbines indicates that the so called 'energy payback time' varies from a few months to one or two years at most. In other words when the wind turbine has operated for this period it has generated enough to produce another wind turbine. A study by the University of Groningen (IVEM, Netherlands) indicates that large wind turbines have smaller energy payback times than small ones. The energy pay-back time of a 10 kW wind turbine varied between 0.5 to 1.5 year, whereas for a 500 kW machine this period reduced to 2 to 3 months [26]. The latter value can be understood by means of the following rough calculation.

Three commercial wind turbines in the range 200-500 kW gave the following values for the ratio total weight/capacity: 110 to 130 kg/kW. Assuming in a first approximation that all these kilos are steel, which costs about 15 MJ/kg to produce [27], each kW installed takes about 1,800 MJ to produce. On the other hand, it takes the kW installed about three months to produce this 500 kWh. It is to be noted on the one hand that more efficient steel production methods exist (with plasma- smelt technology the energy intensity lowers to 9 MJ/kg [27]), but on the other hand that the production and installation of the wind turbine itself also costs some energy.

The <u>conclusion</u> is that the energy to produce and install a (medium-sized) wind turbine can be generated by the turbine in <u>less than a year</u>.

5.2 Emissions

An overview of the CO_2 emissions of different energy technology systems had been prepared by US DOE. The total fuel cycle has been taken into account, i.e. including the emissions during fuel extraction, construction and operation of the systems, and converted them into metric tons of CO_2 per GWh produced by the systems. The results are presented in Table I.

Table I The CO_2 emissions of different electricity production technologies [28]

	Emissions by Energy Production Stage (Metric Tons per GWh)			
Technologies	Fuel Eextraction	Construction	Operation	Total
Conventional Coal Plant	1 0	1.0	962.0	964.0
AFBC Plant	1 0	1.0	960 9	962.9
IGCC Electric Plant	1 0	1 0	748.9	750.9
Oil Fired Plant	-	-	726.2	726.2
Gas Fired Plant	-	-	484.0	484.0
Ocean Thermal Energy Conversion	NA	3 7	300.3	304.0
Geothermal Steam	0 3	1.0	55.5	56.8
Small Hydropower*	NA	10 0	NA	10.0
Boiling Water Reactor	1.5	1.0	5.3	7.8
Wind Energy	NA	7 4	NA	7 4
Photovoltaics	NA	5 4	NA	5.4
Solar Thermal	NA	3 6	NA	3.6
Large Hydropower	NA	3 1	NA	3 1
Wood (sustainable harvest)	-1509 1	2.9	1346.3	-159.9

(-) Missing or inadequate data for analysis, estimated to contributed <1%
(NA) Not Applicable
* This analysis considered construction of new dams According to a recent Federal Energy Regulatory Commission report there is 8,000 MW of small hydropower under construction or projected, much of it involving refurbishing or refitting existing dams, which would substantially reduce small hydropower's CO_2 impact.

As long as wind turbines operate in a society where the predominant portion of the electricity is being generated by burning fossil fuels, each GWh generated by wind power prevents the emission of a certain amount of CO_2 and other gases. The exact value of this prevented emission depends on the mix of generating stations in the country concerned.

With 5% energy penetration in 2000, and a capacity factor of 0.26 (1,518 MW producing 3,457 GWh/year) Halberg calculates a reduction of 1,356 ton SO_2, 2,875 ton NO_x and 2,282 kiloton CO_2 [7] for the Netherlands. This corresponds to 0.39 ton SO_2/GWh, 0.83 ton NO_x/GWh and 660 ton CO_2/GWh. The values are much lower than for a lot of other countries, because of the relatively large number of gas-fired stations in the Netherlands.

With 1,500 MW and a capacity factor of 22% (2,891 GWh/year) Van Wijk calculates the following reductions: 728 ton SO_2, 3,081 ton NO_x and 1,989 kiloton CO_2 [41]. This corresponds to 0.25 ton SO_2/GWh, 1.07 ton NO_x/GWh and 688 ton CO_2/GWh, which means less SO_2, more NO_x and about the same amount of CO_2 per GWh compared to the Halberg study.

It will be clear from the differences in the results that the prevented emissions by wind power are not constant per GWh, but strongly depend on the emission assumptions taken. With the present intense international discussion on global climatic change and the effect of emissions it is envisaged that gradually the emission limits of fossil-fired power stations will be decreased. As a result the relative emission reduction (in ton/GWh) of wind power will decrease as well.

It seems more productive to regard wind as an emission-free source with a certain cost price (see chapter 6.5), which competes with other emission-free sources. In the case of a coal plant for example, this means (a.o.) that the cost for removal of SO_2, NO_x and CO_2 are to be added before a comparison can take place. This brings us to the conclusion that it is somewhat superfluous to calculate the emission prevented by installing wind power, because the future production mix is unknown. For the readers who nevertheless wish to have an idea of the order of magnitudes, Table II presents values for the EC.

Table II Estimates of prevented emissions by EC wind power (Lysen's estimates, production based on 2000 kWh/kW [43])

		2000	2010	2040
ASSUMPTIONS				
Installed capacity	MW	4,150	12,100	100,000
Production	GWh	8,300	24,200	200,000
SO_2 emission	ton/GWh	1.0	0.5	0.25
NOx emission	ton/GWh	1.0	1.0	0.5
CO_2 emission	ton/GWh	750	650	600
RESULTS				
SO_2 reduction	ton	8,300	12,100	50,000
NOx reduction	ton	16,600	24,200	100,000
CO_2 reduction	kton	6,225	15,730	120,000

6. ECONOMIC ASPECTS

In discussing the economic aspects of wind energy the generating cost and the value of the energy produced clearly have to be treated as different subjects.

The best way of comparing wind energy with its alternatives is to base the comparison on the total costs of the different energy technologies. The 'value' of wind energy is equal to the total cost of the alternatives.

The total costs of energy generation are built up of the following categories [33]:

1. government cost,
2. external cost,
3. private (or economic) cost.

The cost categories 1 and 2, which are also called 'social cost', include all elements a society has to pay for in order to have access to a particular energy source at comparable environmental impact and taking into account all stages of the energy production chain. In this report we will assume the private cost to be the same as the generation cost.

The issue of social cost became subject of public discussion after publication of the EC study conducted by Hohmeyer [32]. In different countries studies were initiated to translate the results of this study into specific national situations and needs.

The question of comparing total cost of wind energy with other sources is illustrated in Fig. 10.

The generation costs of wind energy are determined by:

1. the total initial investment cost;
2. economic parameters such as interest rate, amortization period, etc.;
3. system efficiency of the wind turbine system;
4. wind speed; 3 and 4 leading to expected annual average power output;
5. technical availability;
6. O&M cost;
7. life time.

6.1 Generation cost of wind energy

In this paragraph the different factors determining the generation cost will be discussed. This will not been done in terms of absolute figures but merely in terms of relative figures and trends.

6.2 Investment cost

Investment cost are to split in wind turbine manufacturing cost, transport, installation and infrastructure costs (civil works such as roads, foundations) which include the cost of grid connection.

The relation between these cost factors vary very much with the condition of the soil, distance between wind turbine generation plant and transformer station. These are so specific that no general conclusions can be drawn.

In Fig. 11 a typical example of the relative cost breakdown of a Danish wind turbine in an American wind farm is depicted. It may be concluded that the non-machine component of the total cost is quite important in finding ways of reducing investment cost.

The American experience learned that a considerable reduction of turn key cost can be realized in the course of time (Fig. 12). The question however is to which extent the American experience can be used as a reference case for other countries. The following qualitative analysis addresses some typical differences.

It is most likely that the reduction of turn key cost of the American wind power is mainly due to the reduction of machine cost rather than a reduction of infrastructure cost. From the beginning the latter cost already formed a minor part of the total cost. Probably the same applies to the project development cost (procurement, building permits, commissioning, etc.). The wind turbines, however, were quite small in terms of installed power and the first machines combined a poor performance and high cost. The high cost were not due to manufacturing cost but market scarcity.

In Europe, the first wind farms consisted of relatively mature wind turbines of which the cost already were minimal because the market supply side was large compared to the demand side.

With the exception of Denmark the first MW-size wind farms in Europe consisted of machines with an installed power of around 250 kW each.

Project development cost and in a lot of cases also the infrastructure cost (foundation, transformer stations, access roads) in Europe form a large portion of the total cost (up to 50%). Through planning experience and careful siting these cost potentially can be reduced considerably.

It must however be born in mind that the more the best wind energy sites are utilized the more difficult it becomes to reduce cost.

The observations apply to the present commonly used technology, which are machines up to around 300 kW. From the use of larger machines (500-1,500 kW) it is expected that the project development cost and infrastructure cost per kW can be reduced, however the machines are still in the development stage.

Only some ten 500 kW prototypes (or first commercial units) exist, whereas the MW-size machines only exist as experimental plants [38]. From the last category it can be said that the machine cost are a factor 3 to 4 higher than the cheapest machines of 300 kW.

For this review paper we will - quite arbitrary - consider a future cost reduction of the turn key cost of large wind energy projects of 20%. One should keep in mind that this reduction can only be achieved on the short term for medium size machines but for MW-size machines it will take considerably longer (5 - 10 years).

6.3 Economic parameters

For the economic analysis to follow we will consider **an economic life time of 20 years,** equal to the commonly used design life time, although the proven technical life time of the best machines is at this moment about 10 years. The reason for choosing 20 years is that in most design criteria 20 years life time for the critical machine components is taken. Research activities contribute rapidly to a more accurate and verified method to design the components for a certain fatigue life time. The interest rate is 0.05.

6.4 System efficiency

The annual average power output of a wind turbine can be expressed as follows:

$$p = a \times \frac{1}{2} \times \rho \times k_E \times V^3 \quad (W/m^2)$$

where: p average power output per m^2 swept rotor area (W/m^2)
a the system efficiency
ρ the air density (kg/m^3)
k_E energy pattern factor. This factor is the ratio between the actual energy content of the wind (e.g. during one year) and the energy of

the wind calculated on the basis of the constant wind speed, equal to the (annual) average value:

$$k_E = \frac{E_{wind}}{\frac{1}{2} \times \rho \times V^3}$$

V is the annual average wind speed (m/s)

The value of k_E for a wind regime in Western Europe is about 1.9 and varies only a few percent with height and deviating shapes of frequency distribution curves.

The average power output per square meter swept rotor area p $(=P/A)$ can thus simply be expressed as: $p=bxV^3$, where b is called the performance factor being proportional to the system efficiency under the condition that the energy pattern factor is constant. b is a measure for the performance quality of a wind turbine. The ECN test station has calculated the value of b from measurements of wind turbines during the period 1981-1988. In Fig. 13 the value of b is plotted against the year of manufacture of the wind turbine.

The maximum value of b which under the most ideal circumstances can ever be achieved is about 0.4. From Fig. 13, it can be concluded that only a few percent improvement of system efficiency can still be realized.

The measured value of b can be used to evaluate the performance of existing wind turbines. Comparing energy production data of wind turbines in different countries, taking into account the local average wind speeds, leads to the conclusion that the performance of wind turbine does not vary very much from type to type and country to country.

The conclusion from this section is that for the present analysis no further improvements of the wind turbine system efficiency will be considered.

6.5 Wind speed

As the wind energy potential is proportional to V^3 it is extremely important to choose a site with a wind speed as high as possible. What is considered as a high potential area for wind energy varies from country to country.

The highest potential areas in Ireland and Scotland have a power density (600 W/m^2) which is almost two times as high as the same areas in Italy and France, while Denmark, the Netherlands and the Northern German plains have large areas of 'medium' potential. Considering the wind turbines cost the same per m^2 rotor area all over Europe, this leads to the conclusion that the generation cost for the areas considered in first instance are proportional to inverse value of the wind energy potential.

Talking about the cost of wind energy in general for an Italian wind energy is 2 times as expensive as for an Irishman or Scotsman.

For the further analysis, we will however consider the Danish - Dutch - North German - East British wind regime as representative. The average wind speed at 10 m height is 5.5 m/s. The yearly energy output of a typical wind farm consisting of typical 300 kW/25m

machines based on this wind speed and a performance factor of b = 0.36 is therefore e = 825 kWh/m² swept rotor area.

6.6 Availability

The availability is the fraction of the time in one year that the wind turbine is able to generate energy. The total outage time, whether planned (O&M) or unforseen (failures, incidents, accidents) is included.

It is only allowed to use data on the availability if they are based on large number of machines and an operation period of some years. Only the USA and Denmark at this moment have enough wind turbines to provide these data.

Further the development stage of the wind turbine should be considered in assessing availability. From other fields of technology, such as the aircraft industry, data on availability (and reliability) are available from which the wind turbine community can learn. Figure 14 for instance depicts how maintenance and repair costs of aircraft engines of one type develop in the course of time after market introduction.

Availability can be considered proportional to the inverse of these cost. One observes a steep increase of the cost during the first 2 years after introduction. This is mainly due to 'kinder-diseases': small technical failures etc. It is only possible to arrive at the classical learning curve by solving all the technical problems arising during the initial phase of application, without introducing major changes in the turbine concept. For, each time the basic concept is changed one will be confronted with a new curve and will be positioned at the beginning of this curve.

Translating this fact to the wind energy technology the question has to be answered: 'Which type of wind turbine is located where on the curve?' Only after this is done on the basis of thorough technology reviews, predictions can be made on the possible improvements of reliability and availability in the near future.

Experiences from the USA learn that the medium size machines (up to 250 kW) have probably reached the state of steady increasing availability. The larger machines (300 kW and up) still are in the initial phase.

Experiences in the USA (Fig. 15) learn that the best machines have reached availability levels of 95% after 5 years. To make extrapolations towards the future it is indeed justified to use the performance of the best machines as a reference rather than average data of the total population. In this analysis we will thus consider future availability rates of 95%.

6.7 O&M cost

Yearly O&M cost are often taken as a percentage of the initial investment cost. The electricity companies mostly determine the O&M cost as a fraction of the generation cost per kWh. As most of the information is available in terms of cost per kWh we will use this unit for the further observations. Quoted O&M cost based on practical experience vary from ECU

0.004/kWh for mature European wind turbines to very high figures for failed projects [19]. For the analysis to follow we will assume the O&M cost to be ECU 0.005/kWh.

6.8 Lifetime

An economic lifetime of 20 years will be used here for the analysis of generation cost, as already was pointed out in paragraph 6.2.

6.9 Generation cost

Different from the method used in [31] and methods often used by utility companies, the generation capacity of a wind turbine will not be based on the load factor and the installed capacity, but on the annual average wind speed and rotor swept area. The reason is that the latter method allows correction of the generation cost for varying average wind speeds.

The generation cost will be estimated for the machines which presently generate electricity at the lowest cost. The concerning machines are those of the 300 kW/25 m category. It will be indicated what the effect of previously mentioned improvements on the generation cost for the near future will be.

The generation cost of wind electricity will be estimated for 4 situations by means of the following simple expression:

$$g = ((c \times R)/(e \times A)) + m$$

where: *g* generation cost (ECU/kWh)
c initial capital cost per m^2 rotor swept area (ECU/m^2)
R annual charge rate on capital
e annual energy output per m^2 rotor swept area (kWh/m^2)
A availability (1)
m average operation and maintenance cost (ECU/kWh)

The annual charge rate on capital R is:

$$R = r/\{1 - (1 + r)^{-n}\}$$

where: *r* interest rate
n period of amortization

The four situations apply for present medium size machines and for MW size machines in a period of 5 to 10 years:

Situation 1:	State of the art in countries like Denmark, the Netherlands, North Germany
Situation 2:	Near future situation for the same countries as situation 1
Situation 3:	Situation 2 for low wind countries like Italy, France, Spain
Situation 4:	Situation 2 for high wind countries like the west of Wales and England, Ireland and Scotland

Table III Summary of economic parameters

	Sit. 1	Sit. 2	Sit. 3	Sit. 4
c (ECU/m^2)	375	300	300	300
r	0.05	0.05	0.05	0.05
V (m/s)	5.5	5.5	5.0	6.0
V (m/s)	6.4	6.4	5.8	7.0
n (years)	20	20	20	20
A	0.9	0.95	0.95	0.95

Further assumptions:

- performance factor b = 0.36
- specific rated power of the medium size wind turbines: 450 W/m^2 swept rotor area
- turn key cost USA (sit. 1): US $1,000/kW
- exchange rate: ECU 1.- = $ 1.20
- m: ECU 0.005/kWh

The following comparison may serve as a verification of the assumptions of the economic evaluation.

Recent figures provided by ELSAM [40] show that the investment cost of wind turbines, which include transport and erection but exclude foundation and grid connection, per kWh produced annually are

0.6 ECU/kWh for a 16 m machine
0.3 ECU/kWh for a 25/30 m machine and
0.2 ECU/kWh for the next generation 35 m machines.

The earlier defined situations 1 and 2 refer to Denmark. Here (c/e)xA is the same parameter, but includes foundation and grid connection.

For situation 1 the value of c/exA is 0.48 ECU/kWh
For situation 2 the value of c/exA is 0.38 ECU/kWh

Table IV The results of the generation cost

Situation	g (ECU/kWh)
1	0.045
2	0.036
3	0.046
4	0.028

At this moment the generation cost of wind electricity is equal to about 40% higher than those of electricity from fossil resources. With slight increase of fossil resources, however, the balance will flip over, something which is likely to occur in the near future.

6.10 Avoided costs

Van Wijk calculates in his thesis the cost avoided by saving fuel, installing less capacity and reducing the cost for SO_2, NO_x and CO_2 removal [41]. A summary of his results, calculated with data for the Netherlands, are shown in Table V.

Table V Avoided costs of wind power
(Note: Dfl values converted at ECU 1 = Dfl 2.32)

		1995	2000	2005	2010
Wind capacity	MW	400	1,000	1,500	2,000
Production	GWh	812	2,029	3,044	4,058
Break-even costs					
Fuel	ECU/kWh	0.024	0.024	0.022	0.023
Capacity	ECU/kWh	0.009	0.007	0.006	0.005
Emission	ECU/kWh	0.019	0.018	0.016	0.015
Total	ECU/kWh	0.052	0.049	0.044	0.043

Comparing these results with the generation cost figures of table IV shows that wind power is close to break-even. It should be mentioned, though, that the majority of the emission reduction costs are for the removal of CO_2, a removal which is still open to debate. If these costs are not accounted for the avoided costs reduce to ECU 0.034/kWh in 1995. Assuming that this cost level is representative for Western Europe, one notes that this is 3/4 of the expected kWh costs of ECU 0.044/kWh in the same area (case 2), and about equal to the expected ECU 0.035/kWh in the windy areas of Europe (case 4).

This conclusion can also be formulated as follows: when CO_2 removal is included, wind power is profitable right now for utilities in the windy areas of Europe, and will be so in the near future for sites with moderate wind regimes. Excluding CO_2 removal, the present situation, will make wind power profitable in the near future for utilities in the windy areas of Europe.

An integral comparison of wind energy with its alternatives can only been made on the basis of the total cost concept. In order to determine the total cost of wind energy the government cost and external cost have to be added.

Government cost comprise:

- R&D support
- Non R&D government support (investment subsidies)
- Tax provisions
- Loan (guarantees)

External cost for wind energy are made up from:

- environmental clean up cost which are virtually zero for wind energy
- economic development cost which are very low for wind energy

- cost connected to supply reliability and security. These are cost to prevent supply disruptions, etc
- system operation cost, related to the potential impact of the wind energy technology on the operation of the electricity supply system, among others the capacity credit

Similar cost categories have to be included in the total cost of fossil energy conversion technologies and nuclear plants. DeAngelis and Rashkin [33] made a first ranking of energy technologies on the basis of total cost. From this analysis it appears that wind energy is one of the cheapest energy generation technologies already now. Table VI indicates their first results.

Table VI Results from a cost analysis

All cost types rated equally		Private cost emphasized	
Electric generation technology	Relative cost units	Electric generation technology	Relative cost units
Oil combustion	33	Fuel cells (natural gas)	38
Nuclear fission	28	Oil combustion	37
Coal	27	Nuclear fission	36
Natural gas combustion	24	Coal	35
Co-generation	23	Ocean energy	34
Fuel cells (natural gas)	22	Photovoltaics	34
Municipal waste	20	Municipal waste	32
Geothermal	19	Co-generation	31
Ocean energy	18	Geothermal	31
Hydroelectric	18	Solar thermal electric	29
Photovoltaics	18	Natural gas combustion	28
Conservation/solar	18	Hydroelectric	26
Biomass	17	Biomass	25
Wind	17	Wind	25
Solar thermal electric	17	Conservation/solar	22

The reason of the advantageous ranking of wind energy is due to the relatively high external and government cost for fossil and nuclear conversion technologies.

7. APPLICATIONS FOR DEVELOPING COUNTRIES AND REMOTE AREAS

In the previous sections the emphasis was on electricity producing machines for grid connection. Electricity drawn from utility grids is only a small portion of the total world's energy needs. In industrialized countries only 20% of the primary energy is converted into electricity with an approximate efficiency of 35% if transport losses are included.

About 80% of the world's population lives in rural areas. Again 80% of the rural residents are not being served by a grid.

Table VII Percentage of rural residents not being served by a grid

Africa	92
Latin & South America	54
All industrial nations	0
All others	70

It therefore is important to also consider the use of wind energy for non grid connected applications. The power range where wind turbines become an interesting option is, say, 0.5 kW to 100 kW. If power packages smaller than 500 W are needed often photo voltaic units are cheaper to use.

As wind turbines have to compete with no energy suppliers at all or with relatively expensive units such as small diesel engines, the economic assessment for these applications results in much higher break-even kWh cost levels.

Typical applications where wind turbine can be used for in rural and remote areas are:

residential/commercial sector:
- lighting
- refrigeration (food and medicine conservation)
- appliances
- telecommunication
- generation for small isolated grids
- water pumping

special remote applications:
- communication stations
- cathodic protection
- light houses
- desalination
- water aeration
- water purification

The following major systems can be distinguished:

- hybrid systems. Wind diesel is the most relevant mix of systems.
- stand-alone units.
- battery charging units.

In remote places in the world where grid connection is not yet available (or will never be available) one has the option to supply power by means of smaller or larger diesel-powered generators. When a wind turbine (or more turbines) is added to the diesel-generator, fuel is saved and when there is enough wind, the diesel engine could even be stopped altogether.

The rationale behind wind-diesel systems is to save as much diesel fuel as possible, while at the same time guaranteeing a similar kind of reliability (or higher) as without the wind turbine.

Wind diesel systems still are not available from the shelf. The economic feasibility, of course depending very much on local circumstances, is a great problem. Substantial developments are needed to improve the situation.

Stand alone units operate without any back-up system and can be used for typical applications where supply and needs can be matched by means of cheap storage systems. Typical examples are electric deep well pumps directly connected to the generator, desalination units, cooling units. These applications are still in the R&D stage. The worldwide technical market potential is considered huge but the market place lacks capital to create a self-sustaining commercial process.

Battery charging units are well known already for decades. These small units (up to 1 or 2 kW) are applied for lighting, telecommunication, off-shore signals, etc. The machines are well developed and a relatively small market sustains the production. The situation could change considerably if rural electrification schemes will be based on individual housing systems rather than local grids. It becomes more and more clear that individual systems are a very good alternative for grid connected systems in rural electrification schemes.

Some projects based on individual houses equipped with photo voltaic units (Philippines, Indonesia) have proved to be very successful. For open windy areas small wind turbines could be a cheaper alternative. However as p.v. systems get cheaper in the future, wind turbines are likely to loose the game on the basis of cost, reliability and O&M needs.

General observations:

- If storage capacity is needed to match varying energy needs and supplies it is always cheaper to store products (water, heat) than electricity.

- All storage systems are expensive (water tanks, batteries). It is important to dimension the capacity of the storage system as small as possible by analyzing the energy supply and demand statistics given a specified system supply reliability.

8. CONCLUSIONS

The wind potential puts no restraints to the widespread use of wind power. The world wind energy potential is at least three times larger than the present world average consumption of electricity (1 TWyr/yr).

There are a number of constraints, however, which cause that probably only a fraction of this potential will be realized, as far as one can judge at this point in time. These constraints take the form of physical and institutional restrictions, environmental considerations, cost aspects and technical limits.

It is estimated that these restrictions reduce the exploitable wind power (according to present thinking) to about 10% of the electricity demand. If e.g. the demand in a sustainable European Community would level off at 230 GWyr/yr, this implies an exploitable wind potential of 23 GWyr/yr, to be generated with a wind capacity of the order of 100,000 MW. The present wind capacity in the EC (January 1990) is 326 MW, of which 254 MW is installed in Denmark, and 40 MW in the Netherlands. The forecast for the wind capacities in the twelve EC countries is 4,150 MW in the year 2000, increasing to 12,100 MW in 2010. This means that in 2010 the contribution of wind is around 1% of the total electricity demand, with the potential to grow to at least 10% of the demand.

With respect to the effects of wind energy on the environment two aspects are mentioned here: the energy costs of producing wind turbines and their contribution to the reduction of CO_2 emissions.

The energy costs turn out to be low: medium scale wind turbines (200-500 kW) generate in less than six months enough energy to produce the materials (mainly steel) of which they are made of. At present most of the energy for producing the steel is released by burning fossil fuels, and this is the only contribution to the CO_2 emissions by wind turbines: 7 tons of CO_2 per GWh of electricity produced by the wind turbines. When the wind turbines generate their electricity in a grid with coal fired power stations, they prevent the emission of (depending on the station efficiency) 750 to 1,250 tons of CO_2 per GWh. This means that the balance is largely positive.

Under the most favourable conditions wind energy is already competitive with other energy sources in terms of generation (economic) costs. If the cost of fossil energy sources increase, also wind electricity generated in less windy areas of Europe may compete with electricity from fossil sources. In the case the comparison is based on total cost (thus including external and government cost) wind energy already is one of the cheapest energy resources available.

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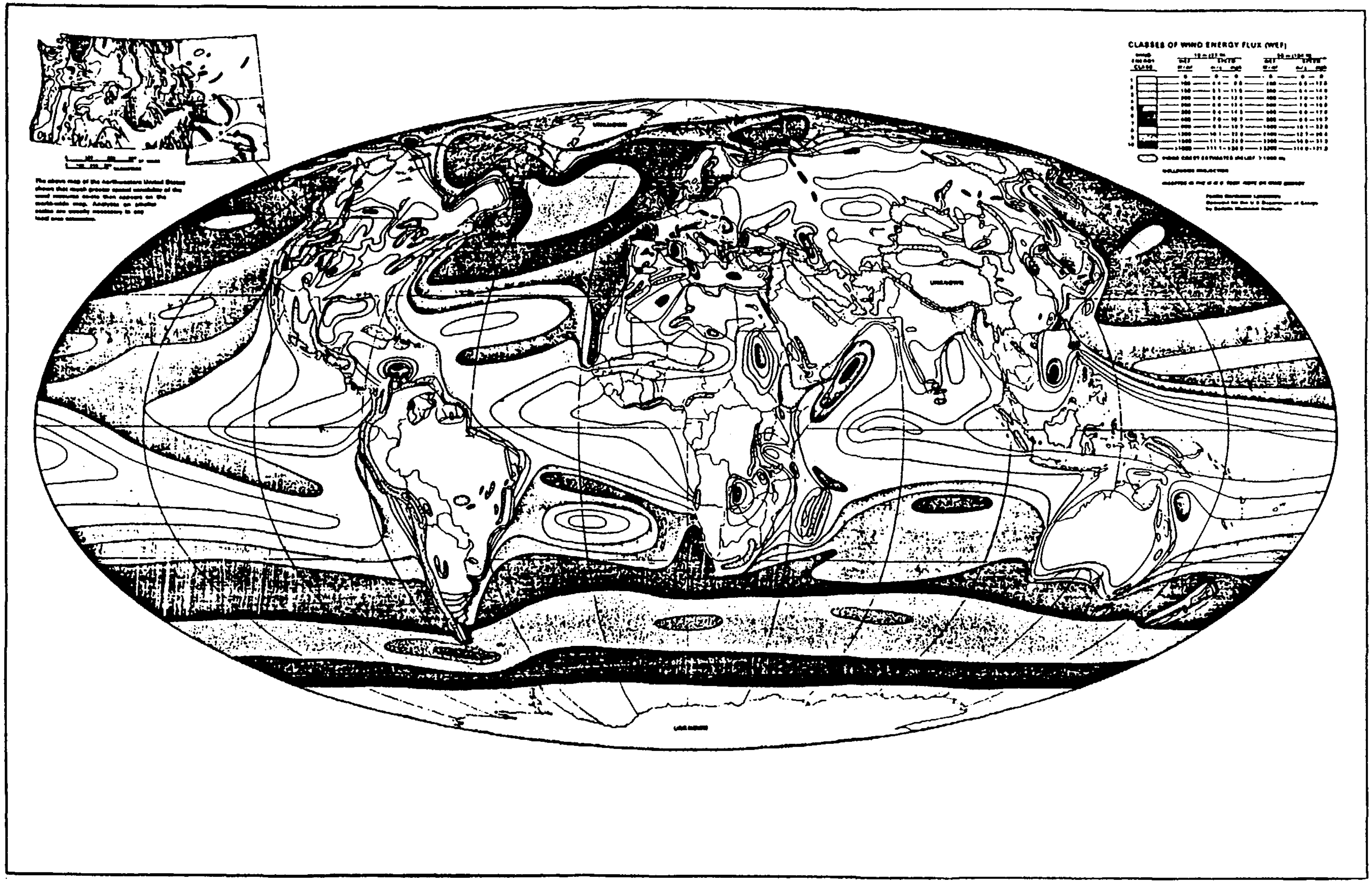
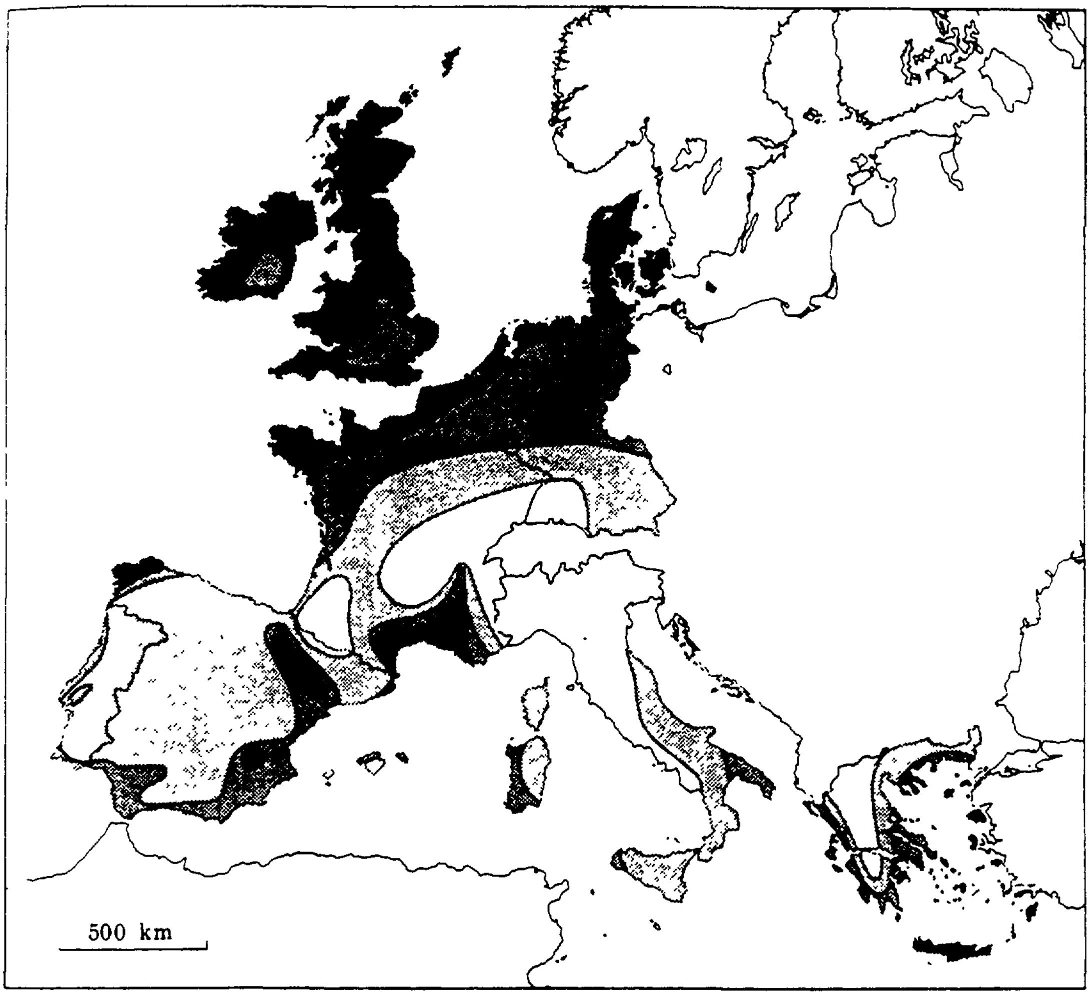


Fig. 1 World wide wind energy resource distribution estimates [34]



Wind resources at 50 metres above ground level for five different topographic conditions

	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Fig. 2 Distribution of the wind resources in the European Communities [8]

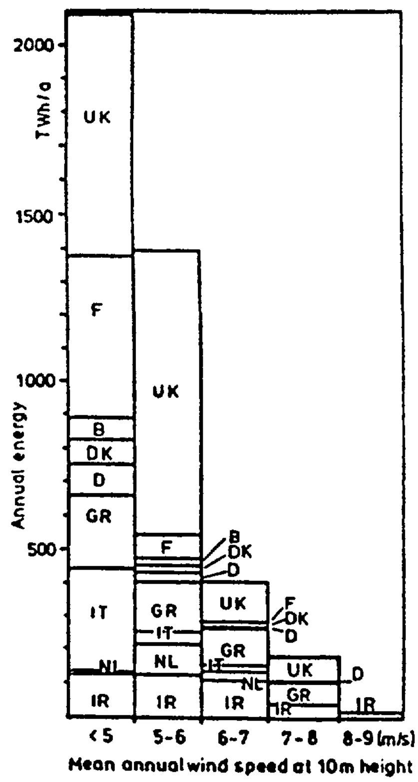


Fig. 3 Potential wind energy contribution from different EC countries for various parts of their wind regimes [4, 19]

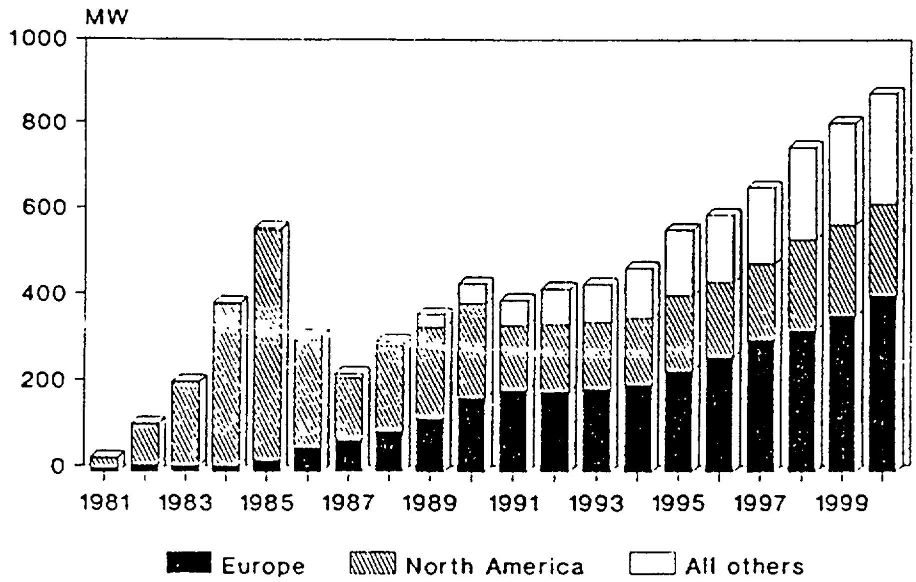


Fig. 4 World wind turbine annual shipments: actual to 1987 and base case forecast [44]

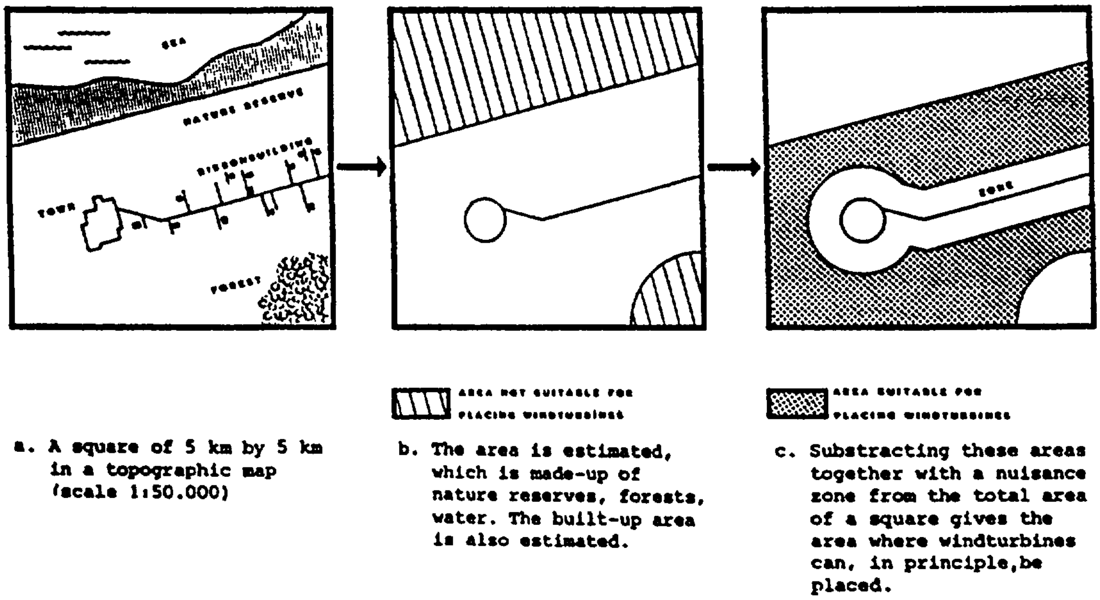


Fig. 5 Different steps in determining the areas suitable for the installation of wind turbines in The Netherlands [10]

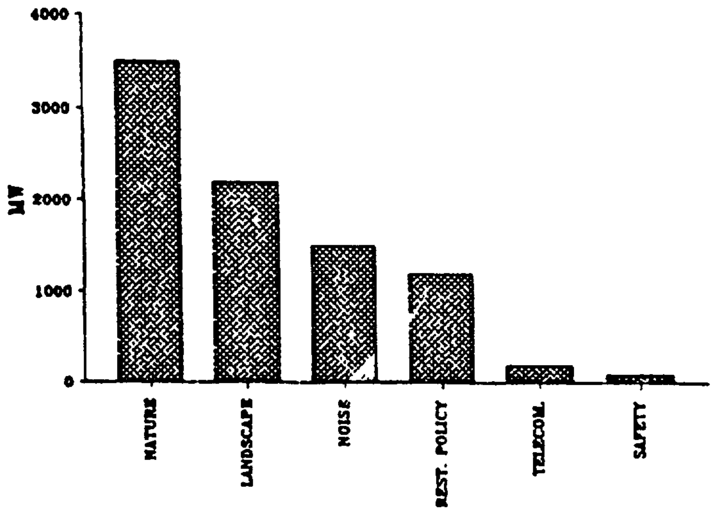


Fig. 6 Theoretical influence of planning constraints to the wind potential in The Netherlands [10]

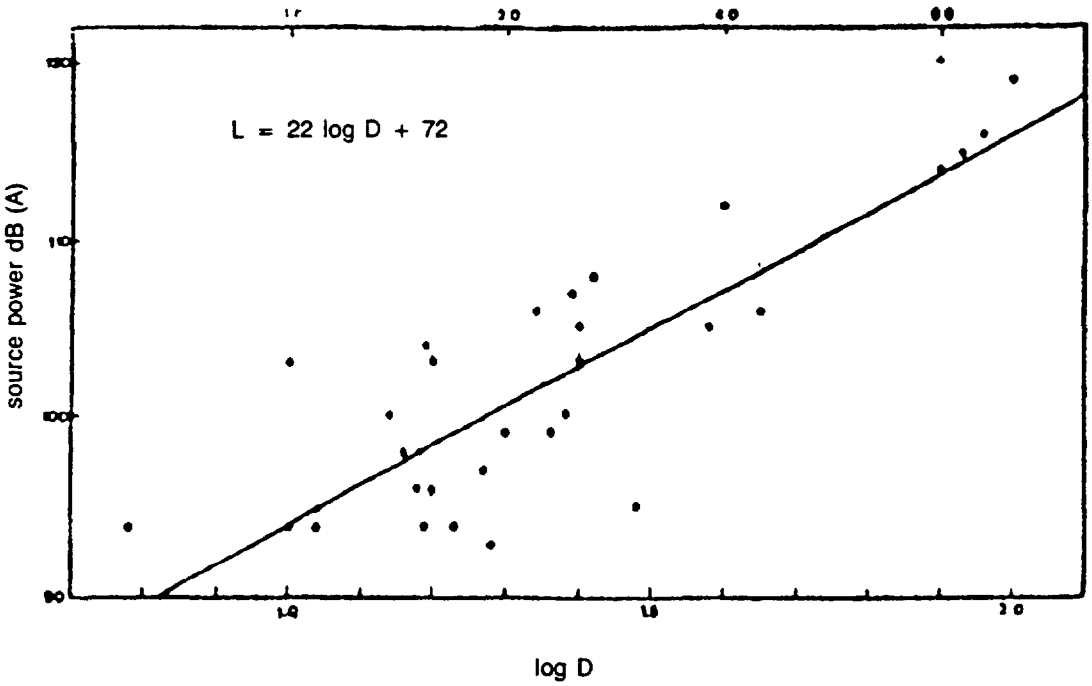


Fig. 7 Measured acoustic emission levels versus rotor diameter [35]

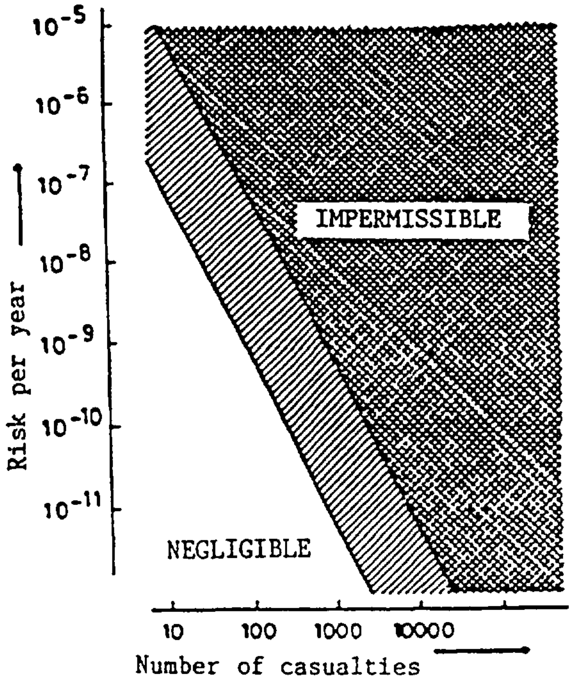


Fig. 8 Safety criteria

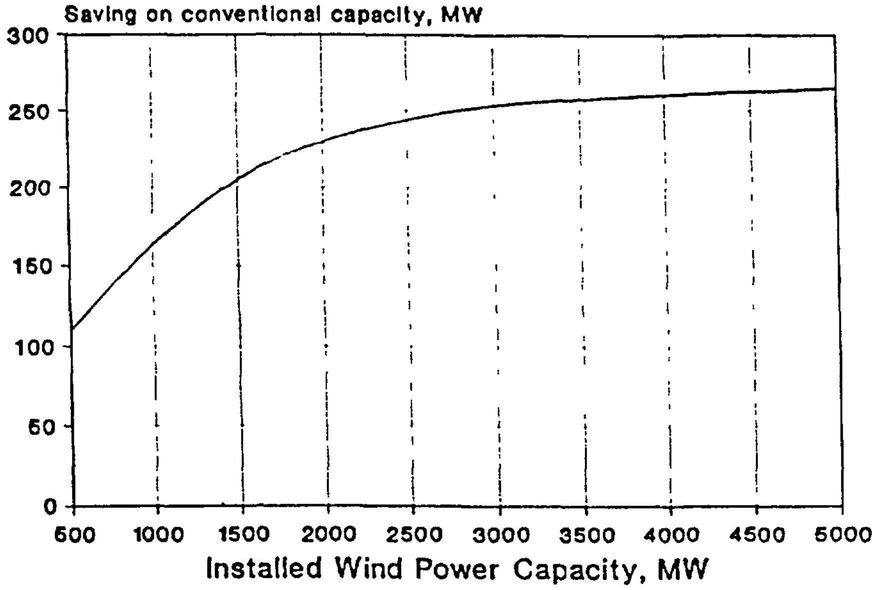


Fig. 9 Capacity credit of wind turbines in The Netherlands [7]

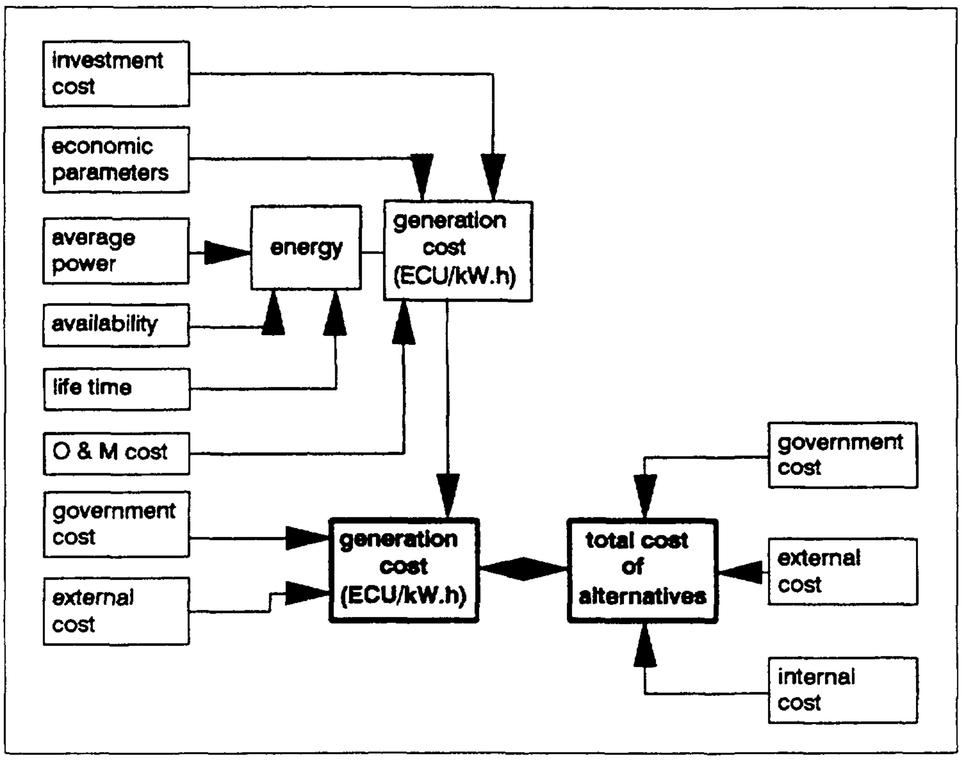


Fig. 10 Comparing generation cost and the value of wind energy

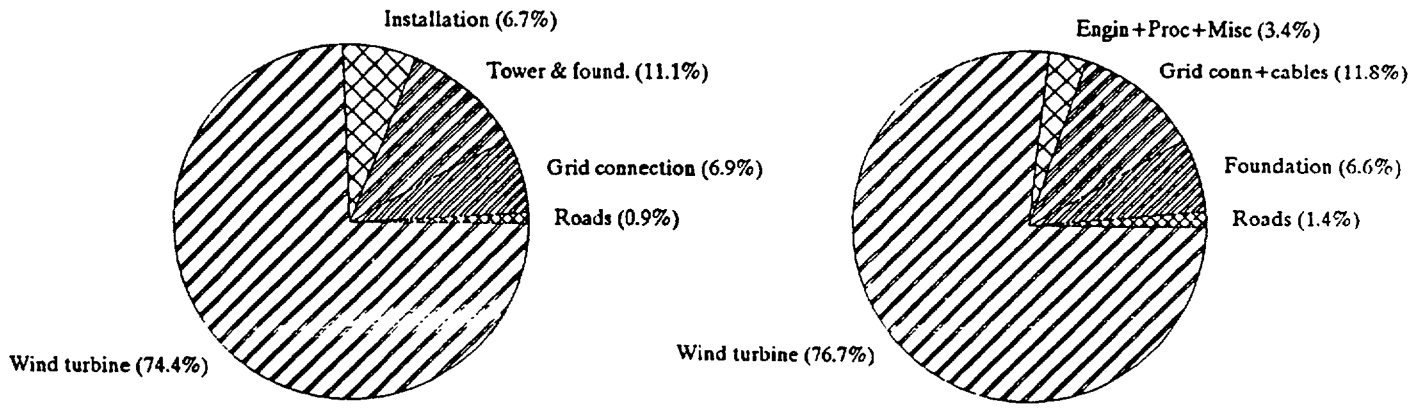


Fig. 11 Cost breakdown of a Danish wind turbine in an American wind farm

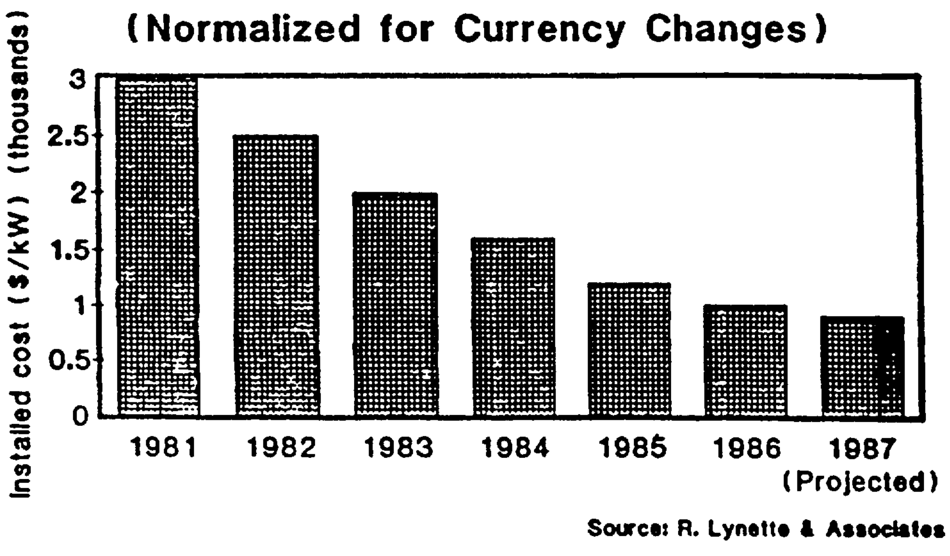


Fig. 12 The development of turn-key cost of American wind farms

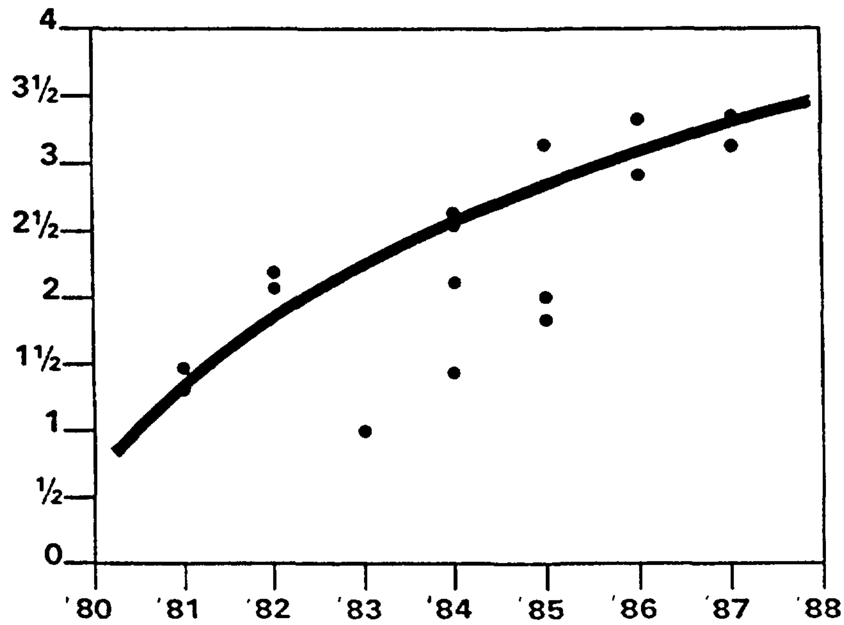


Fig. 13 The development of the performance factor of wind turbines [39]

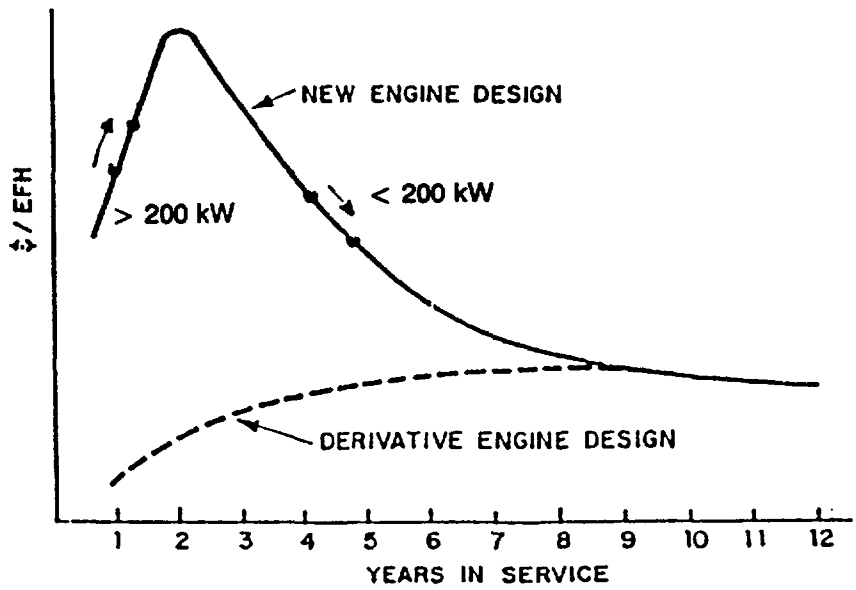


Fig. 14 The maintanance and repair cost of aircraft engines as a function of service life

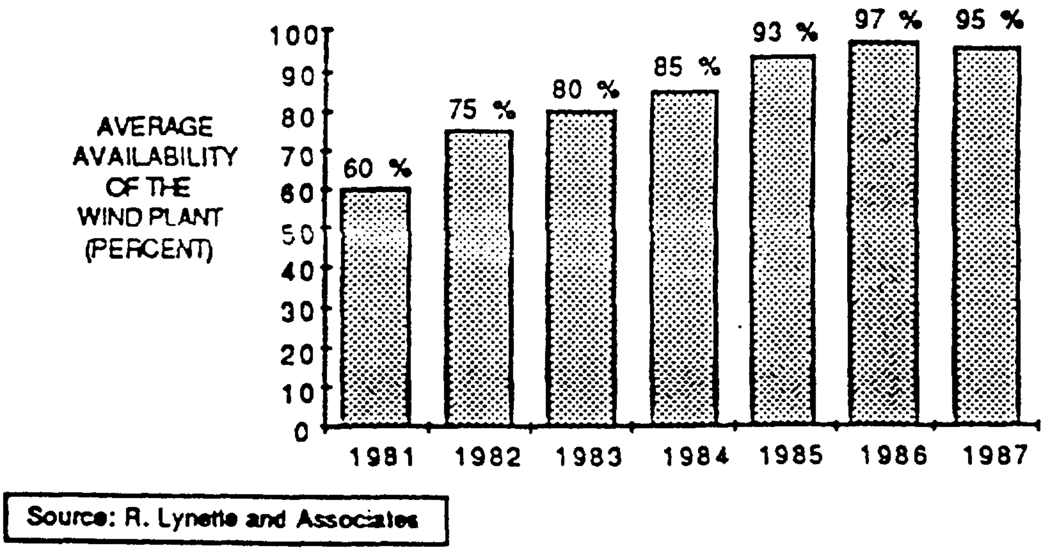


Fig. 15 Availability of the best wind turbines in California

ADVANCED FOSSIL TECHNOLOGIES FOR ELECTRICITY GENERATION

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ABSTRACT: Fossil fuels are, and will continue to be, the energy source for the vast majority of the world's electric power generation. In addition to its abundance, a major attribute of coal that has enabled its use to grow rapidly is the fact that it can be transformed into electricity at relatively low cost. Future global economic growth, particularly in developing countries, will bring large increases in electricity generation and, correspondingly, coal usage. Today, environmental requirements have joined cost reduction as primary considerations in the design and operation of coal-fired power plants, and they are a major driving force behind the new technological directions for coal utilization. This paper provides a summary of the performance, costs, and environmental impacts of selected technologies that are representative of commercially available and emerging, advanced fossil power generating technologies. The authors have attempted to present information for the various technologies on a common basis. This is particularly important when comparing technologies that are at different levels of maturity. In general, the estimates presented in this paper are idealized for representative generating units and are not intended to apply to specific utilities or sites, since site conditions, utility preferences, and national or local requirements will dictate design and cost variations.

1. INTRODUCTION

Fossil fuels are the primary energy source for the vast majority of the world's electric power generation. In many countries, residual fuel oils are used for electric power generation, while in other countries, such as Japan, liquefied natural gas (LNG) is used to fuel the world's largest combined cycle power plants. The proven global reserves of fossil fuels, other than coal, could be consumed by the end of this decade. That reality will place escalating cost pressure on the additional use of these energy sources, and will lead to significantly increased coal usage.

In addition to its abundance, a major attribute of coal that has enabled its use to grow rapidly is the fact that it can be transformed into electricity at relatively low cost. Future global economic growth, particularly in developing countries, will bring large increases in electricity generation and, correspondingly, coal usage. Today, environmental requirements have joined cost reduction as primary considerations in the design and operation of coal-fired power plants, and they are a major driving force behind the new technological directions for coal utilization.

Two key trends have historically characterized coal plant design: increases in efficiency and increases in capacity. The thermal efficiency of coal-fired steam electric generation rose from 5% in the late 1800s to nearly 40% in the late 1960s. This resulted in an 85% reduction in fuel consumption per kilowatt-hour of electricity produced. During the same period, boiler size increased from 50 kW to 1,200 MW, resulting in substantial capital cost reductions due to economies of scale. By the 1970s the diminishing performance returns from the Carnot Cycle were joined by new economic and institutional forces, namely rapidly escalating capital costs, slow demand growth, stricter emission control requirements, and extended licensing and construction schedules. The result has been an abrupt end to the historic trend of declining real cost of electricity from coal. A kilowatt of new generating capacity costs more today (in constant dollars) than it did in 1920. Although the United States of America has probably led this regression, similar trends exist throughout the developed world as we grapple with new societal demands on power production. It is precisely this challenge which the new technologies for coal utilization must address.

The importance of this effort is underscored by the fact that in the United States a new, large, pulverized coal-fired power plant may typically cost US $1.5 billion, with more than 30% of the cost driven by environmental controls. Moreover, these controls have a major impact on plant efficiency and reliability. The principle guiding the development of advanced fossil generating technologies is that sustained environmental improvement will only be effectively achieved when emission reduction and cost reduction compliment each other. This responds to the environmental consensus of society while controlling the cost of energy and keeping its supply secure. Simply stated, the goal is to resolve the policy conflict between coal use and environmental quality.

In light of the above, this background paper provides a summary of the performance, cost and environmental impacts of selected technologies that are representative of commercially available and emerging, advanced fossil power generating technologies, with particular emphasis on emerging coal-based technologies. The list of emerging technologies is not intended to be all inclusive, but does represent a broad range of options. In compiling this data, the authors have attempted to present information for the various technologies on a common basis. This is particularly important when comparing technologies that are at different levels of maturity. For some of the advanced fossil technologies, the information presented represents the author's best judgement of the rationally achievable cost and performance.

2. ENERGY RESOURCES AND RESERVES

Coal is the most abundant fossil resource in the world. Figure 1 indicates that coal represents approximately 90% of all conventional fossil reserves [1]. It is also the dominant resource in the USA, China, and the USSR Projections by the Conservation Commission of the World Energy Conference [2] for the evolution of world energy utilization indicate the following (as demonstrated in Fig. 2):

- Peaking of oil consumption by 2000, followed by a steady decline.
- A steady increase in nuclear power generation to a 2060 level that is approximately five times greater than 1990 totals.
- A steady increase in natural gas consumption that begins to level off by mid-century.
- A rapid escalation in coal consumption resulting in consumption levels in 2060 that are three times greater than today. Further, coal consumption is projected to outstrip natural gas by a factor of 2 and oil by a factor of 3 by 2060.

The challenge posed by the above forecast is how to stimulate the use of coal for the production of low cost energy while protecting the environment. These requirements can be translated directly into the need to maximize the thermodynamic and economic efficiency with which the world uses coal.

3. TECHNOLOGIES FOR ELECTRICITY GENERATION

Several current and advanced fossil power technologies were selected for review. These technologies are listed below and are representative of the broad range of power production options expected to be available within the next several decades.

- Gas turbine (GT)
- Combined cycle (CC)
- Fossil steam boiler
- Advanced fossil steam boiler
- Atmospheric fluidized-bed combustion (AFBC)
- Pressurized fluidized-bed combustion (PFBC)
- Coal gasification combined cycle (GCC)
- Fuel cell
- Integrated gasification fuel cell
- Direct coal-fired combined cycle
- Gasification/PFBC hybrid
- Binary rankine cycle
- Magnetohydrodynamic generation (MHD)

A consistent set of design assumptions was made in order to develop comparative estimates of performance, costs, and environmental impacts of the various fossil power technologies. In general, the estimates presented in this paper are idealized for representative generating units and are not intended to apply to specific utilities or sites, since site conditions, utility preferences, and national or local requirements will dictate design and cost variations. In developing these estimates, an effort was made to forecast probable capital expenditures associated with commercial-scale projects.

3.1 General assumptions

- The base case coal for this evaluation is a low sulfur (1.0% as received) bituminous coal. Several technologies are also evaluated with a higher sulfur content coal (2.4% as received). For emissions estimates, low and high sulfur bituminous coal compositions are assumed as given in Table I.

Table I Base coal characteristics used in the analysis

Ultimate analysis, wt. % (as rec.)	Low sulphur	High sulphur
Moisture	10.0	10.0
Carbon	66.3	65.1
Hydrogen	4.3	4.2
Nitrogen	1.0	1.0
Chlorine	0.4	0.4
Sulfur	1.0	2.4
Oxygen	6.4	6.3
Ash	10.6	10.6
Heating value (MJ/kg, LHV)	25.4	25.4

- All plants are grass-roots (green-field) facilities with no constraints on available land, water, and other resources.
- Delivery of coal is by rail for both the low and high sulfur bituminous coal cases.
- Natural gas is available at the site at the power block pressure requirements. Natural gas is assumed to be 100% methane with a heat content of 50 MJ/kg, LHV.
- Condenser backpressure is 0.065 bar (closed-loop cooling tower).
- Solid wastes are disposed of in off-site facilities.

3.2 Environmental assumptions

For technically preventable or controllable atmospheric emissions, e.g. sulfur dioxide and nitrogen oxides, the technologies are evaluated on the basis of emission ceilings that are currently the most advanced standards in place, or are expected to become the most stringent standards. The most stringent regulations for sulfur dioxide and nitrogen oxides (290 mg/Nm^3 for SO_2 and 150 mg/Nm^3 for NO_x) that are currently discussed for implementation in Nordic countries are chosen as the upper technical limit (German standards for NO_x emissions from new power plants are already set at 200 mg/Nm^3). The emission standards presently active in several OECD countries (400 mg/Nm^3 for SO_2 and 650 mg/Nm^3 for NO_x) form the basis of a medium emission case. Unregulated emissions, a situation that may prevail outside the OECD region, are presented for comparison.

3.3 Technology specific assumptions

This section provides a brief description and key assumptions for each technology. Simplified flow diagrams for most of the technologies are shown in the accompanying figures. The data in the figures refers primarily to European design conditions, although both USA and European design conditions are addressed in the following text.

- In gas turbines, hot combustion gases are used directly to turn the turbine which drives the generator. The most important measure for achieving higher efficiencies is to increase the inlet temperature of the gas turbine (TIT) before the first stator blade from the current 1,100-1,200°C range to approximately 1,400°C in the last decade of consideration (2010-2020). The problems that have to be solved concern the material in the gas turbine blades and other parts. Today, the designs are based on metal cooled by air or on cooling the cooling air. The next steps are directed towards metal materials being fully steam cooled, as well as single crystal alloys and, in the long run, ceramic materials. Some current gas turbines control NO_x emissions with water injection, while others use dry, low NO_x burners. Future gas turbines are expected to include improved dry, low NO_x burner designs.

- Combined cycles combine a gas turbine with a steam turbine. Several different configurations are possible – unfired combined cycles, fully-fired combined cycles, combined cycles with pressurized steam generator, etc. This paper considers only the unfired combined cycles where electric power is generated first by a gas turbine and then by producing steam from the hot gas turbine exhaust gases to run the steam turbine. Figure 3 shows a simplified flow diagram for a typical combined cycle with a current gas turbine (TIT = 1,170°C). Steam is generated in a double pressure heat recovery steam generator (HRSG). Typical steam conditions are 8 MPa/525°C for the main steam, and 0.5 MPa/200°C for the secondary steam. Reheat steam cycles (10 MPa/540°C/540°C) can be used to improve the overall efficiency if the gas turbine exhaust gas temperature is high. Very often two gas turbines, each with its own HRSG, is combined with one steam turbine. NO_x control is through steam injection or dry, low NO_x burners.

- The fossil steam boiler plants, shown schematically in Fig. 4, use steam cycle conditions of 17 to 24 MPa, with superheat and a single reheat to 540°C. The subcritical steam conditions are representative of USA conditions, while the supercritical steam conditions are more representative of European conditions with increased emphasis on higher efficiencies. The high sulfur coal case uses a wet-limestone forced-oxidation spray tower flue gas desulfurization (FGD) system and an upstream baghouse. The low sulfur, moderate emissions case uses a slurried-lime spray dryer system and a downstream baghouse. The low sulfur, stringent emissions case incorporates a wet-limestone FGD system and an upstream baghouse. The stringent emissions cases incorporate selective catalytic reduction (SCR) for NO_x control.

- The advanced fossil steam boiler plant incorporates a 31 MPa/590°C/590°C/590°C steam cycle. For the high sulfur case it uses a single module, commercial advanced limestone-gypsum FGD technology and an upstream baghouse. The low sulfur case use two 50% flow lime spray dryer modules and a baghouse downstream. The low sulfur, stringent emissions case incorporates a wet-limestone FGD system and an upstream baghouse. The stringent emissions cases incorporate SCR.

- The atmospheric fluidized bed (AFBC) cases assume a single boiler, circulating bed design with in-bed injection of limestone to control SO_2 emissions and a baghouse for particulate control. A simplified heat balance diagram for a typical AFBC plant is shown in Fig. 5. The steam cycle conditions are 24 MPa/540°C/540°C. The stringent emissions cases incorporate non-selective catalytic reduction (SNCR).

- The pressurized fluidized bed (PFBC) cases assume the combined-cycle configuration using a single PFB vessel. A simplified heat balance diagram for a typical PFBC plant is shown in Fig. 6. The steam cycle conditions are 24 MPa/540°C/540°C. Approximately 20% of the total power is generated by the gas turbine. Control of SO_2 is by limestone injection and control of particulate is through cyclones and a baghouse. The stringent emissions cases incorporate non-selective catalytic reduction (SNCR).

- The coal gasification combined cycle (GCC) cases use a generic gasification process, two advanced gas turbines (TIT = 1,340°C), and a single steam turbine. Fig. 7 shows a simplified flow diagram for a fully integrated GCC with an oxygen blown gasifier. Fully integrated means that the gas turbine air compressor supplies air to the air separation unit, and most of the nitrogen from the air separation plant is mixed with the clean coal gas prior to combustion in the gas turbine. Then the mass flow through the gas turbine is nearly the same as in the case of natural gas firing and no adjustment of the compressor is needed. Approximately 60% of the total power is generated by the gas turbine. The steam process consists of a single reheat cycle with steam conditions of 13 MPa/540°C/540°C. NO_x emissions are usually controlled by the nitrogen reinjection. For the stringent emissions cases additional NO_x control through steam injection or fuel gas moisturization is needed. Sulfur is sold as a by-product.

- Fuel cells are electrochemical devices that convert chemical reaction energy directly into electric energy. Fuel cells are classified into the following categories according to the type of electrolyte used in the cell: PEFC (polymer electrolyte), AFC (alkaline), PAFC (phosphoric acid), MCFC (molten carbonate), and SOFC (solid oxide). The operating temperatures of these fuel cells range from 80°C for PEFC up to 1000°C for SOFC. Fuel cells can be used in base load as well as in partial load, with little loss in efficiency. In this paper, the fuel cell case assumes a natural gas-fueled, molten carbonate design. Figure 8 shows the arrangement for a larger fuel cell or a series of 2 MW units. The carbon in the desulfurized natural gas is converted to hydrogen due to the reformer and the shift. The hydrogen-rich gas then fuels the fuel cell. The exhaust gases are directed first through an expansion turbine and then used to generate steam. Due to the low operation temperature (650°C) the fuel cell has negligible NO_x emissions (and no SO_2 emissions).

- The coal gasification fuel cell design assumes an advanced coal gasification process which is integrated with the molten carbonate fuel cell power block. Sulfur is sold as a by-product. The arrangement is similar to that shown in Fig. 8, except that the coal gasification process provides the hydrogen-rich gas for the fuel cell. Coal gasification fuel cells would be constructed as large central station units, rather than smaller, dispersed units.

- The direct coal-fired combined cycle operates with run-of-mine coal. The concept, with a current gas turbine (TIT = 1,140°C), is shown in Fig. 9. In this case the usual combustor of a natural gas-fired gas turbine is replaced by a pressurized pulverized coal combustor with molten ash removal. Vaporized alkali are removed by getter materials arranged behind the molten ash separator. The combustor needs water cooling. This and the increased auxiliary power demand lowers the efficiency compared to a natural gas-fired combined cycle. However, the efficiency is still expected to be higher than for a coal gasification combined cycle plant. The stringent emissions cases incorporate selective catalytic reduction (SCR) for NO_x control. The desulfurization systems are similar to those described in the fossil steam boiler plant case.

- The binary rankine cycle combines a topping rankine cycle with potassium as the working fluid with a bottoming water rankine cycle. In a coal-fired boiler wet potassium steam (0.22 MPa/850°C) is generated which drives a potassium turbine. Then the potassium vapor is condensed in a potassium/water condenser by evaporating water. The steam is superheated and reheated in the boiler to 20 MPa/560°C/560°C. NO_x and SO_2 control systems are similar to those described in the fossil steam boiler plant case.

- The gasification/pressurized fluidized bed hybrid cases assume an air-blown fluidized bed gasifier with the char-fed PFBC generating high pressure steam and hot combustion gas/oxygen for the combustion turbine. Steam conditions are 12 MPa/540°C/540°C and the gas turbine inlet temperature is 1,260°C.

- The MHD plant is a first-generation, open-cycle, high temperature, enriched-air design which generates electricity directly from hot gas flowing through a magnetic field. Figure 11 shows a simplified flow diagram for a typical MHD power plant. A potassium carbonate seed is used to achieve the required hot gas electrical conductivity. Sulfur is captured as potassium sulfate. A formate process regenerates the potassium carbonate seed. Sulfur is converted to calcium sulfate for disposal. Most of the electric power is generated by a conventional steam cycle with conditions of 17 MPa/540°C/540°C. SCR is used to control NO_x emissions.

3.4 Overall thermal efficiencies

For fossil power generating technologies, a key technical characteristic is the overall thermal efficiency, or net generating efficiency. This efficiency is defined as the net electrical energy produced per unit of energy input as fuel (on a lower heating value basis). Higher efficiencies mean that less fuel is required per unit of electricity produced, thus reducing both the fuel costs and the related emissions.

The trends in overall thermal efficiencies are shown in Fig. 12. Technologies based on the use of gas turbines (Brayton cycles) show significant improvements over the period 1990 to 2020 due to the introduction of new, advanced gas turbines with higher turbine inlet temperatures. In addition to simple cycle gas turbines, these improving technologies include combined cycles, pressurized fluidized bed combustion, and coal gasification combined cycles. For some mature Rankine cycle technologies, such as fossil steam boiler plants, essentially no further increase in efficiency is anticipated. Efficiencies are presented for technologies at the time they become commercially deployable. For example, fuel cells are not expected to be commercially available before 2010, therefore no values for efficiencies are presented for the 1990 to 2010 time periods.

4. ENVIRONMENTAL ASPECTS OF ELECTRICITY GENERATION

Emissions of SO_2 and NO_x from fossil power generating technologies for the time periods 1990-2000, 2000-2010, and 2010-2020 are shown in Fig. 13 and 14, respectively. The upper point indicates a situation of unregulated emissions, while the lower point refers to a situation characterized by stringent regulations.

Coal gasification-based technologies remove sulfur compounds prior to combustion and produce an elemental sulfur by-product, thereby reducing the performance and cost penalties associated with more stringent SO_2 emission controls. Therefore, the coal gasification-based technologies have been designed to meet emission limits that are significantly lower than the stringent standard. Technologies that use limestone-based sorbents for post-combustion removal of SO_2 are also capable of meeting more stringent emission controls, however, the sorbent requirements and solid waste production are rapidly increased.

Lower temperature processes, such as fluidized-bed combustion, produce less thermal NO_x and can frequently meet even the most stringent emission requirements without the need to add expensive selective catalytic reduction equipment. Combustion turbine-based processes can greatly reduce NO_x emissions by dilution of the fuel with water or steam injection to reduce peak combustion temperatures. NO_x emissions from fuel cells are exceptionally low due to the low temperature, non-combustion nature of the process.

Emissions of CO_2 from fossil power generating technologies for the time periods under consideration are shown in Fig. 15. Although Fig. 15 shows only CO_2 emissions, the same overall trend would expected if all greenhouse gases (on a CO_2 equivalent basis) were included. Emissions of CO_2, per unit of electricity production, are a function of the carbon content of the fuel and the overall thermal efficiency of the plant. High carbon content fuels such as coal emit nearly twice as much CO_2 as natural gas. For a given fuel, the emissions of CO_2, are inversely proportional the the overall plant efficiency. Note that more stringent emission standards generally lead to slight reductions in efficiency, and therefore higher emissions of CO_2. Coal-based technologies that use limestone sorbents for SO_2 removal will have slightly higher emissions of CO_2 due to calcining of the limestone.

4.1 CO_2 removal from fossil power plants

The feasibility of significantly reducing CO_2 emissions from present and future fossil fuel-fired power plants has recently been investigated by EPRI and IEA [4]. The objective of the study was to prepare detailed engineering and economic evaluations of CO_2 removal, recovery and disposal from an existing 500 MW fossil steam boiler power plant and from a grass-roots 400 MW coal gasification combined-cycle (GCC) power plant. The evaluation assessed the incremental impact of reducing CO_2 emissions on the design, thermal efficiency, and capital, O&M, and levelized cost of power generation for both plants. The scope of the evaluation included CO_2 removal (nominally 90%), CO_2 compression, and transportation by pipeline to the ocean for disposal. The design coal for the plants was a high sulfur bituminous coal.

4.2 Fossil steam boiler power plant retrofit

The CO_2 removal process selected for the fossil steam boiler plant retrofit was Fluor's Econamine FG process, a high capacity, monoethanolamine process with proprietary corrosion inhibitors. Large quantities of low pressure steam (approximately 40% of the total steam flow) must be extracted from the steam turbine for regenerating the solvent. The existing steam turbine could not be operated with such a large extraction flow and was replaced in the study by a two turbine configuration. A back pressure turbine was used to supply low pressure steam for the Econamine FG strippers, while a smaller condensing turbine utilized the remaining steam flow for power generation. In addition, the existing wet limestone flue gas desulfurization process had to be upgraded to remove most of the SO_2 to prevent degradation of the CO_2 removal solvent.

Results of the study indicated that the net power output of the fossil steam boiler power plant was reduced from 513 to 336 MW (or by about 35%), with a corresponding decrease in net efficiency from 36.7% to 24.0% (LHV), after addition of the CO_2 scrubbing and disposal equipment. Incremental fossil steam boiler plant capital cost, including the cost of replacement power, is approximately US $1,900 per original net kW. The major cost items are the CO_2 pipeline and disposal systems, and the cost of replacement power.

4.3 Gasification combined cycle power plant

The Selexol™ process, a selective physical absorption process, was selected for use with the GCC plant. Pressurized raw gas (consisting primarily of carbon monoxide and hydrogen, with smaller amounts of CO_2) from the Texaco quench gasifiers was sent to a two-stage shift conversion reactor, where essentially all of the carbon monoxide was reacted with steam to form additional CO_2 plus hydrogen. The sulfur compounds were then selectively removed in the first Selexol™ absorber. CO_2 was removed in a second Selexol™ absorber, and then recovered by staged flashing of the rich solvent. The product gas, containing essentially pure hydrogen, was then fired in the combined cycle power plant. The energy penalty for removal and recovery of CO_2 from pressurized coal-derived fuel gas is significantly less than that for removal from atmospheric pressure flue gas due to the reduced volume of gas being treated and the use of a physical absorption process which eliminates the need for low pressure stripping steam.

Compared to a GCC plant without CO_2 removal, the net power output from the GCC plant with CO_2 removal was reduced from 432 to 379 MW (or by only about 12%), while the net efficiency was decreased from 37.4% to 29.9% (LHV). Incremental GCC plant capital cost, including the cost of replacement power, is approximately US $1,200 per original net kW. It is important to realize the fact that even though the cost of *removal* of CO_2 from a GCC plant is significantly lower than that from a fossil steam boiler plant, the total incremental costs associated with *disposal* of the CO_2 from the GCC plant are approximately equal to the costs of disposal of CO_2 recovered from a fossil steam boiler plant. As disposal costs are significantly higher than removal costs, CO_2 removal and disposal from both types of plant are extremely high.

4.4 CO_2 disposal

A number of alternatives have been suggested for ultimate disposal of the recovered CO_2, including deep ocean disposal, injection into depleted oil and gas wells, and enhanced oil recovery. The EPRI study assumed that the recovered CO_2 would be pipelined 500 kilometers overland to the ocean and 160 kilometers offshore for disposal at 500 meters below sea level. An analysis of the environmental aspects of ocean disposal was outside the scope of this work. However, should ocean disposal prove to be environmentally unacceptable, it is important to note that the costs and compression power requirements developed for ocean disposal in the EPRI study are judged to be reasonable estimates for disposal in large depleted natural gas fields. The capital cost for the offshore portion of the pipeline is roughly equal to the cost of improvements required to use the depleted gas wells for long term CO_2 storage.

4.5 Cost Impact of Removing CO_2 From Fossil Fuel-Fired Power Plants

Scrubbing CO_2 from the stacks of fossil steam boiler power plants is an extremely costly form of CO_2 emissions reduction. Based on the costs developed in the EPRI study, the annual cost (annual capital charges plus all operating, maintenance, and fuel costs) to achieve a reduction of 20% from USA fossil steam boiler power plants by the year 2000 would be approximately US $34 billion. Scrubbing CO_2 from the stacks of ALL existing USA coal-fired power plants could result in a capital cost ranging from US $450 billion to US $750 billion (depending on the cost of replacement power). Its full-scale implementation would result in increasing the cost of coal-fired power by a factor of 2.0 to 2.6.

As would be expected, the cost impact of constructing future GCC plants with CO_2 removal facilities is less than the cost impact of scrubbing CO_2 from the stacks of fossil steam boiler power plants. However, as discussed earlier, major CO_2 disposal cost items such as the compressors and pipeline are essentially the same for either type of plant. Relative to a conventional GCC power plant, the cost of electricity would be increased by a factor of 1.6 to 1.7.

5. ECONOMICS OF ELECTRICITY GENERATION

Capital costs for each of the fossil power generating technology are shown in Table II. Technologies based on the use of gas turbines show cost reductions over the 1990 to 2000 time period, while technologies based on conventional steam cycles do not show any significant cost reductions. Capital cost include owner's costs, but exclude allowance for funds used during construction (AFUDC, or sometimes called interest during construction). Owner's costs include prepaid royalties, preproduction (or startup) costs, inventory capital (fuel storage, consumables, etc.), initial cost for catalysts and chemicals, and land.

Fig. 16 shows the cost of electricity for each technology based on a single, consistent set of economic assumptions, without regard for international differences in systems of taxation and finance. The overall generation cost, or cost of electricity (COE), includes the following components:

- Capital cost
- Operating and maintenance costs
- Solid waste disposal cost
- Fuel cost

These estimates are understood to be approximate, since construction costs, cost of capital, plant lifetimes, operating costs, and fuel costs will all vary with location and over time. An effort is made to estimate not only current costs but also projected costs.

All costs are presented in constant January 1989 USA dollars. The economic premises used to develop the COEs are as shown in Table III.

Table II Evolution of plant capital costs

	1990-2000	2000-2010	2010-2020
FOSSIL			
Gas turbine	340	325	310
Combined cycle	550	535	520
Fossil steam boiler (L)	1150-1430 (*)	1150-1430 (*)	1150-1430 (*)
Fossil steam boiler (H)	1150-1470 (*)	1150-1470 (*)	1150-1470 (*)
Adv fossil steam boiler (L)		1350-1600 (*)	1350-1600 (*)
Adv fossil steam boiler (H)		1350-1650 (*)	1350-1650 (*)
Pressurized FBC		1340-1370 (*)	1325-1355 (*)
Atmospheric FBC	1370-1400 (*)	1370-1400 (*)	1370-1400 (*)
Coal gasification comb cycle	1450-1460 (*)	1435-1450 (*)	1420-1435 (*)
Fuel cell			1120
Integr gas fuel cell			1300
Direct coal comb cycle			1150
Gasific./PFBC hybrid			1350-1400 (*)
Binary Rankine cycle		1500-1770 (*)	1500-1700 (*)
MHD			1450-1550 (*)

Share of owner's costs in investment costs

10% for fossil fuelled
15% for nuclear fuelled
15% for renewables

(L) = low sulphur fuel
(H) = high sulphur fuel

(*) Denotes the generation cost range due to different emission standards

Table III Economic assumptions used in the analysis

General inflation rate	0.0%/year (constant dollar)	
O&M cost escalation rate	0.0%/year (constant dollar)	
Project book life	30 years	
Real cost of capital	10%/year	
Yearly operating hours	6570	
Fuel prices	**mill/kwh$_e$**	**Real escalation rate %**
High sulphur coal	3.7 - 8.8	0.5
Low sulphur coal	4.1 - 12.5	1.0
Natural gas	7.9 - 16.4	2.5

Note that ranges of fuel prices have been assumed. Actual fuel prices will vary significantly due to site-specific production and transportation factors, and differences in government energy policies.

Generally, the advanced technologies are more efficient, but they may also have higher capital costs (at least initially). The higher capital cost is offset by lower fuel costs due to better efficiency. Gas turbine and combined cycle power plants have very low capital costs, but use a premium fuel which will likely be subject to significantly higher escalation rates.

6. CONCLUSIONS

The more advanced coal technologies will produce significantly lower emissions and solid waste per kilowatt-hour than conventional coal-based technologies, while generating electric power at competitive prices. Progressive improvements in overall plant thermal efficiencies are a significant factor in accomplishing these results. This culminates in a very dramatic efficiency improvement with the integrated gasification fuel cell technology. Compared to a fossil steam boiler plant with flue gas desulfurization, the gasification fuel cell unit has the potential, when developed, to provide an efficiency improvement of more than 35%.

In addition to efficiency improvements, many of the advanced coal technologies are inherently capable of reducing emissions due to process configurations or conditions such as removal of sulfur components prior to combustion, lower combustion temperatures, or by the use of non-combustion technologies such as fuel cells.

With a few exceptions, the levelized costs of electricity for the current and advanced fossil power technologies fall within a relatively narrow band. Emission controls add about 20% to the cost of electricity from a fossil steam boiler plant. Gasification fuel cell plants offer a potential reduction in the cost of electricity of about 20% relative to other coal technologies with moderate emission controls.

Stringent emission controls can increase the cost of electricity by up to 12% compared to moderate emission controls. This increase can be as little as 2% for most gasification-based technologies.

Although useful for comparative purposes, levelized cost of electricity is not always a valid parameter for selection of the optimum technology. The economic analysis results presented in this paper are based on assumed constant capacity factors. In actual practice, technologies with better efficiencies will likely be dispatched at higher capacity factors compared to less efficient plants, thus further reducing the cost of electricity from that plant.

Fuel costs, along with efficiencies, will also influence the actual plant capacity factors and choice of power technologies. In an era of relatively low gas and oil prices, low capital cost technologies such as combined cycles appear to be the preferred choice for many utilities. However, when the opportunities for phased construction are coupled with escalating emission control requirements and projected gas and oil prices, more and more electric utilities in the USA are incorporating the advanced clean coal option of GCC as the most economic approach to their capacity expansion plans. This is likely to ultimately lead to integrated energy facilities capable of translating coal-derived synthesis gas into a variety of products including, but not limited to, electricity. In addition to coal, such facilities could similarly process carbonaceous refuse and biological wastes – both increasingly difficult by-products of our urbanized and industrialized societies.

Fully integrated energy facilities could be adapted to produce a mixture of electricity, heat, fuels and marketable products. This achievement would present an opportunity to expand coal use beyond conventional applications – for example, to reduce petroleum use in the industrial, residential, commercial and transportation sectors. Development of such plants depends upon the successful blending of a variety of clean-coal technology building blocks. Such a facility could ultimately move beyond the efficiency constraints of the Carnot Cycle by integrating fuel cells, for example, as the electricity production process.

To the extent technology provides increased efficiency in the conversion of coal to usable energy, it will have a beneficial global impact on CO_2 and N_2O generation. In the event that greenhouse warming is substantiated and reducing CO_2 growth becomes a policy imperative, this will provide a powerful additional argument in favor of more rapid development and global deployment of advanced fossil technologies for power production.

A number of international organizations have been working on the development of new high efficiency, low emission technologies for generating electricity from coal. Many of these advanced technologies incorporate power cycles that go beyond the thermodynamic limits of the Rankine steam cycle, and are expected to be commercially available within the next decade. If these development efforts are successful, they should provide important technological breakthroughs to help reduce the cost and environmental impacts of electric power generation.

The last decade of the 20th century and the first decades of the 21st will pose a period of major economic, technical, organizational, and cultural change for world coal users and producers. While these changes pose many challenges, they also bring even greater opportunities. Whether it will be the best of times or the worst of times will, to a large measure, be dependent on how technology is used to respond to these changing circumstances.

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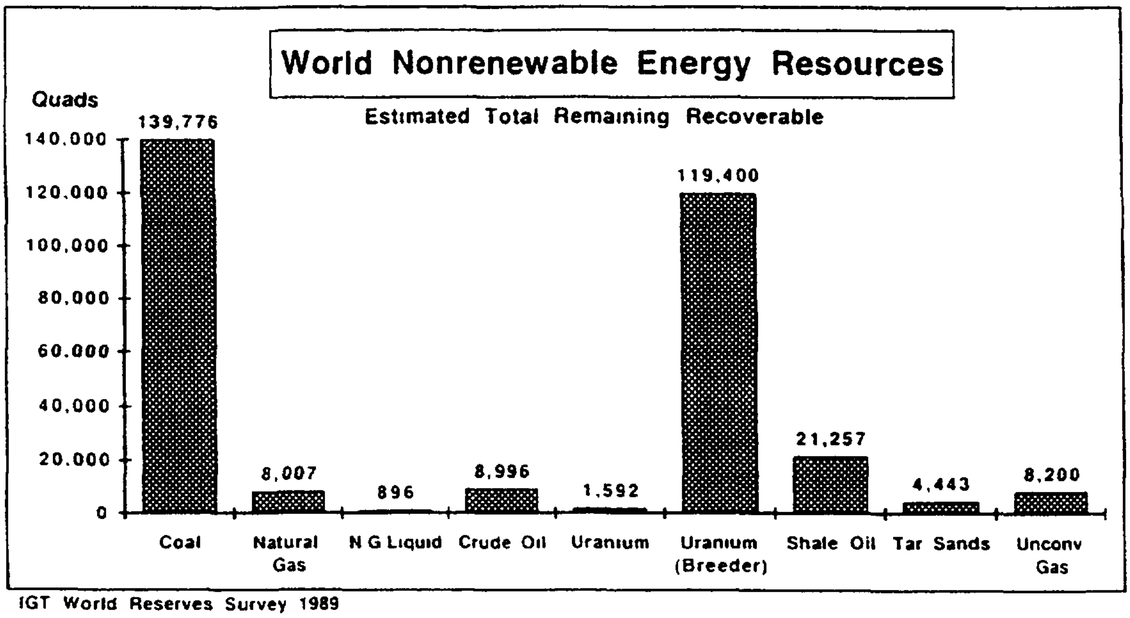

Fig. 1 World non-renewable energy resources.

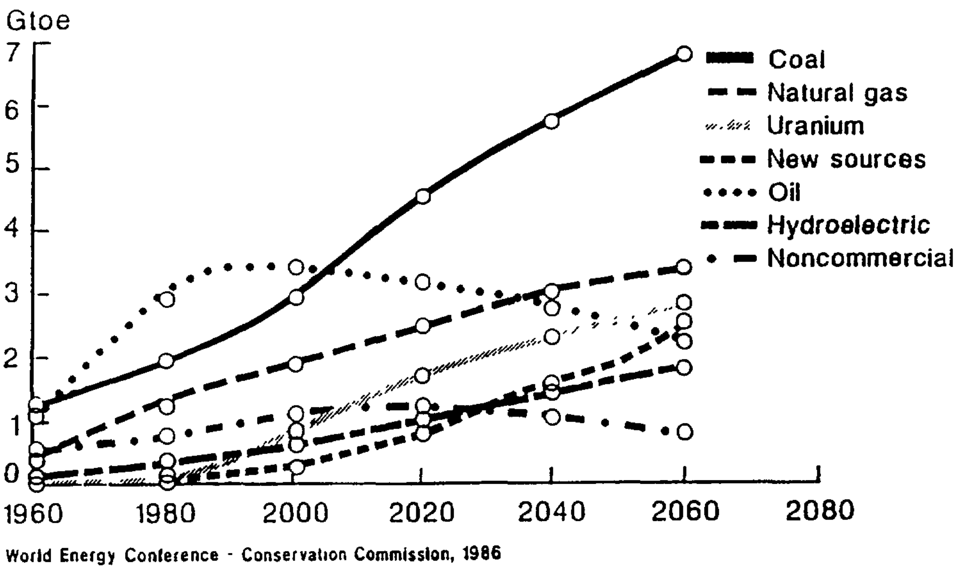

Fig. 2 Evolution of world energy utilization.

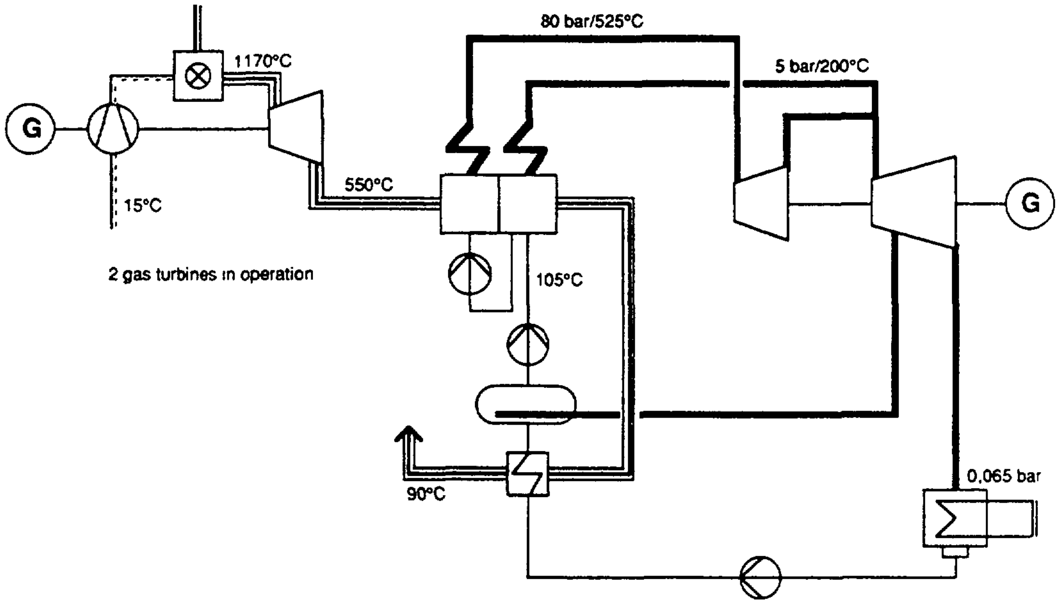

Fig. 3 Combined cycle (natural gas fired).

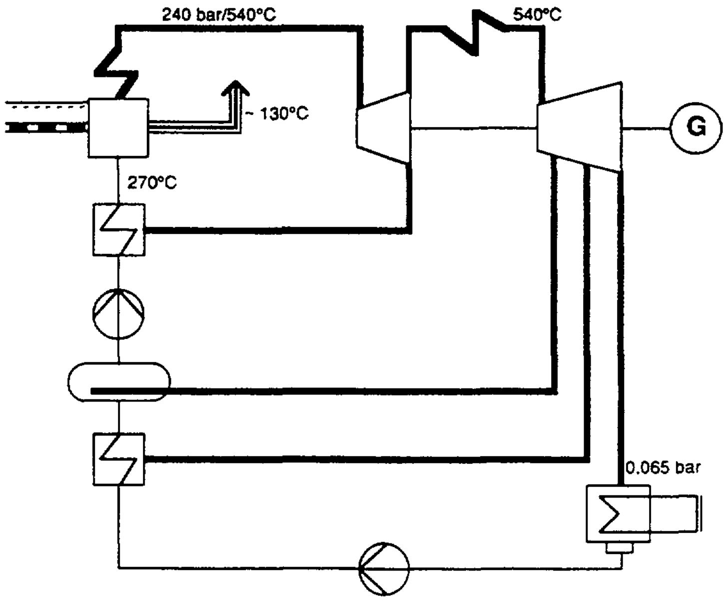

Fig. 4 Fossil steam boiler plant.

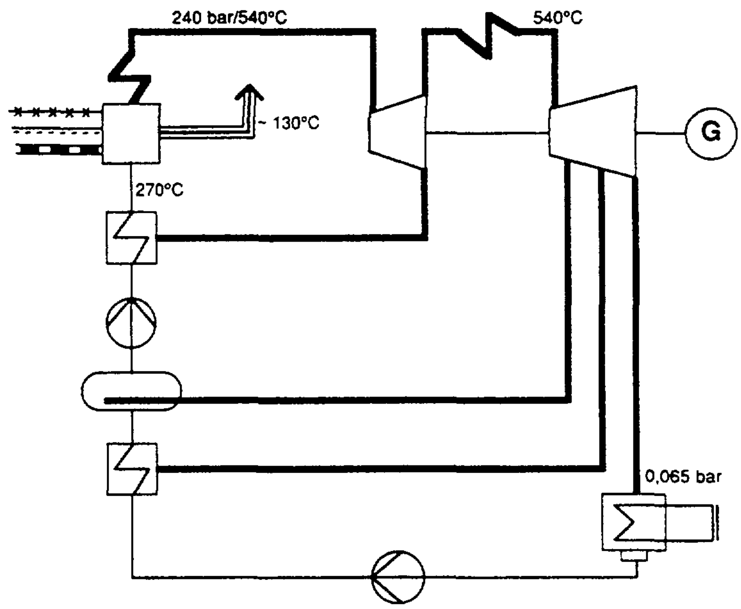

Fig. 5 Atmospheric fluidized bed (AFBC).

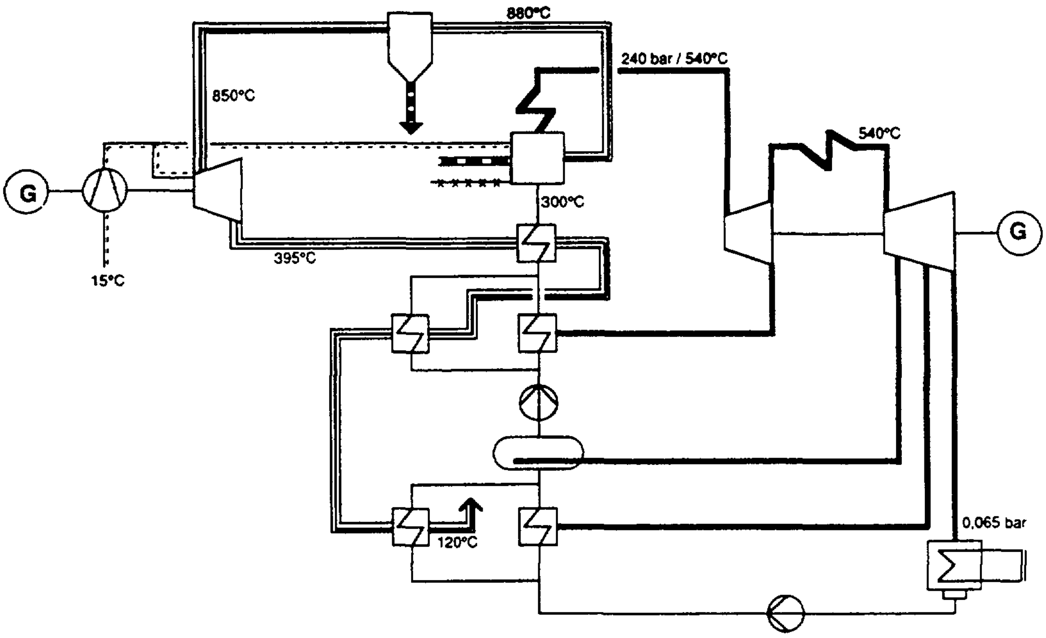

Fig. 6 Pressurized fluidized bed (PFBC).

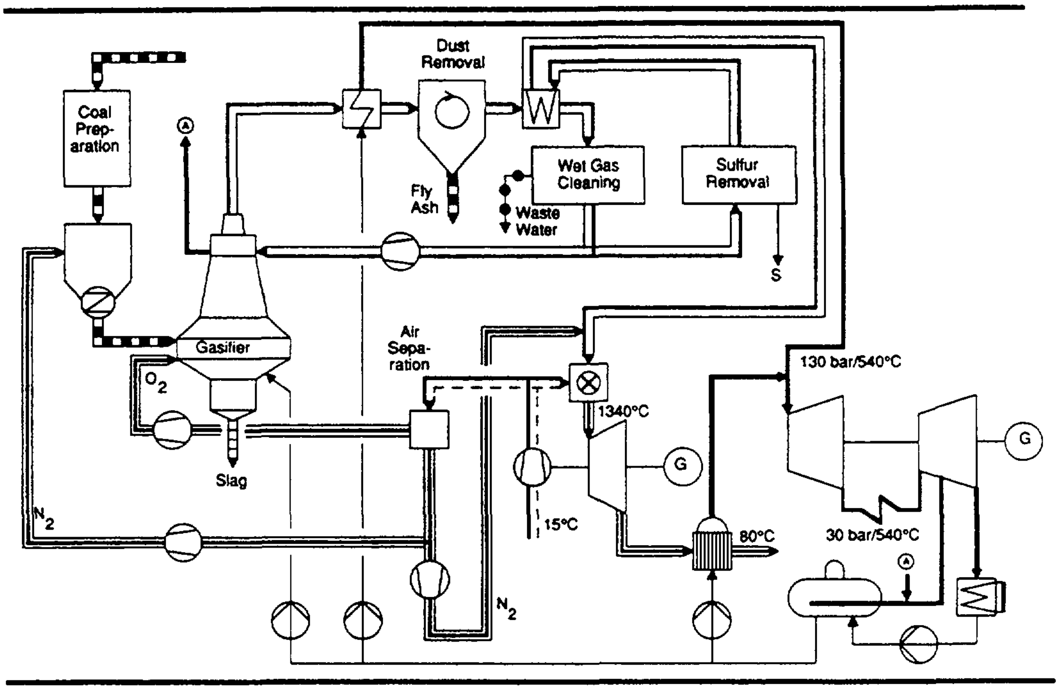

Fig. 7 Fully integrated coal gasification combined cycle (IGCC).

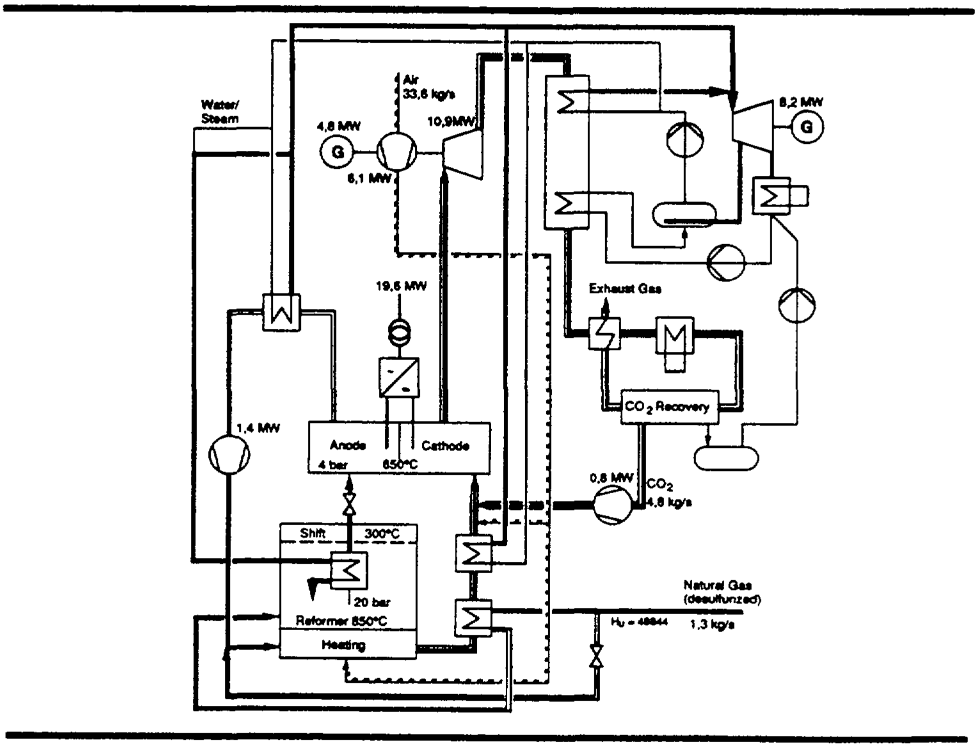

Fig. 8 Molten carbonate fuel cell (natural gas fueled).

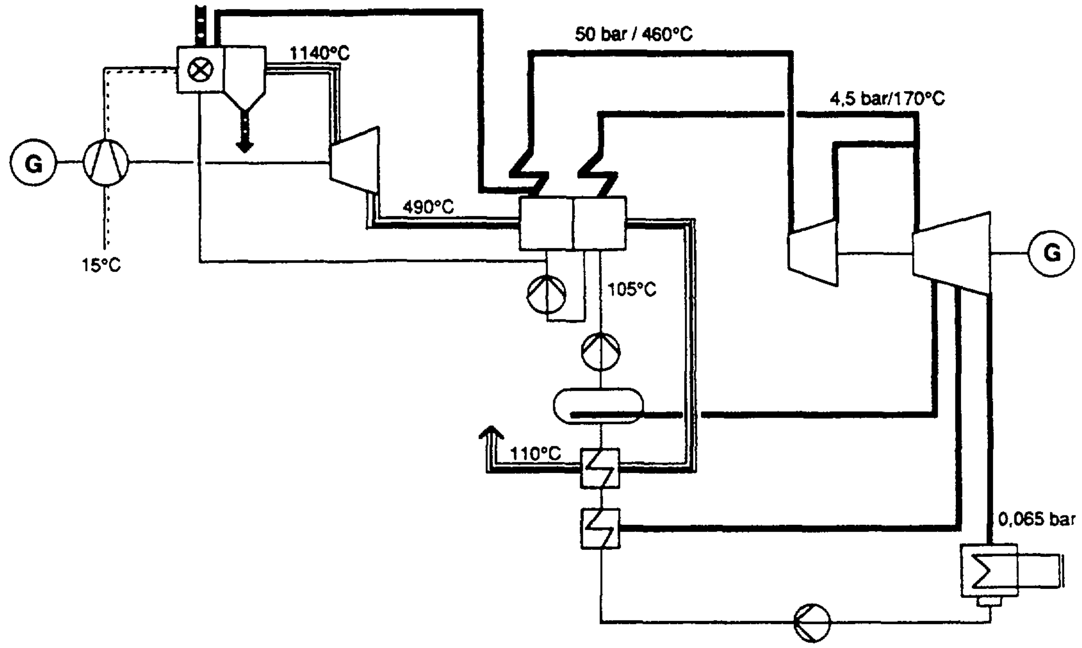

Fig. 9 Direct coal fired combined cycle.

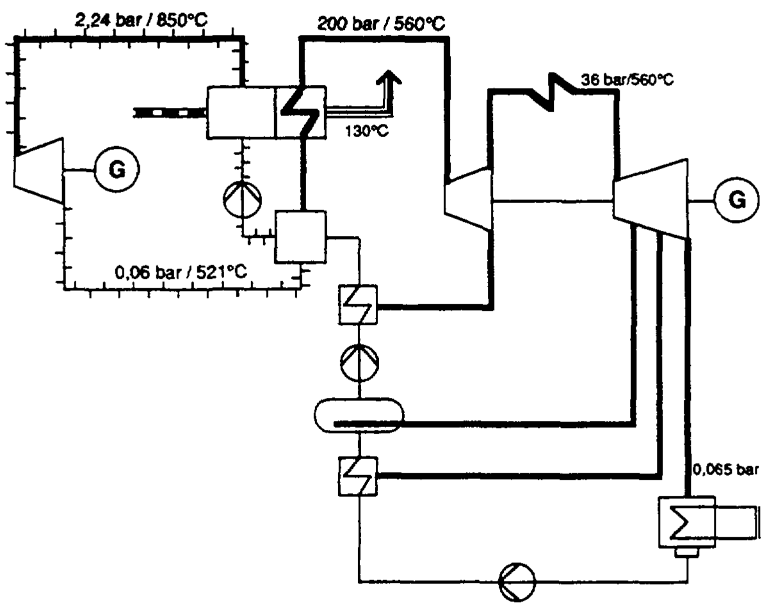

Fig. 10 Binary Rankine cycle (BRC).

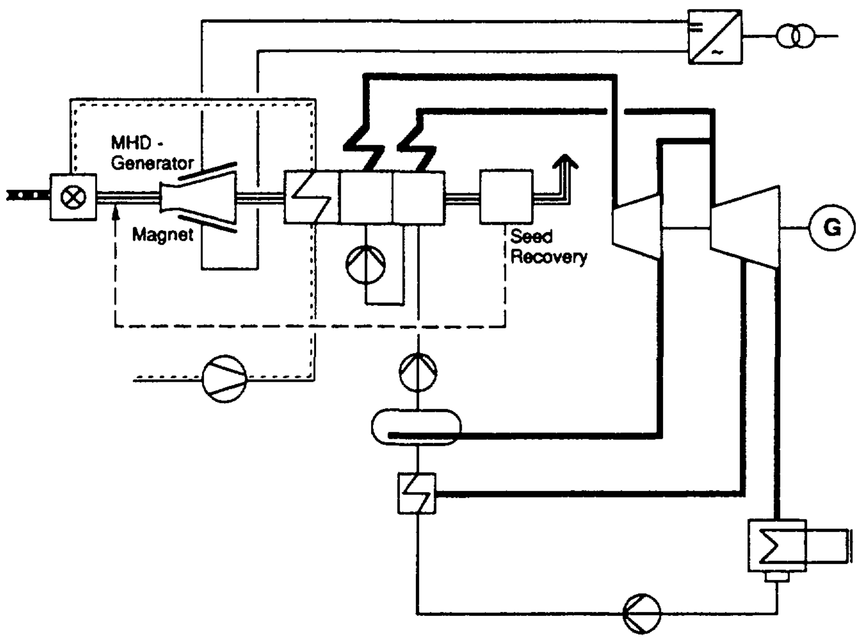

Fig. 11 Magnetohydrodynamic generation (MHD).

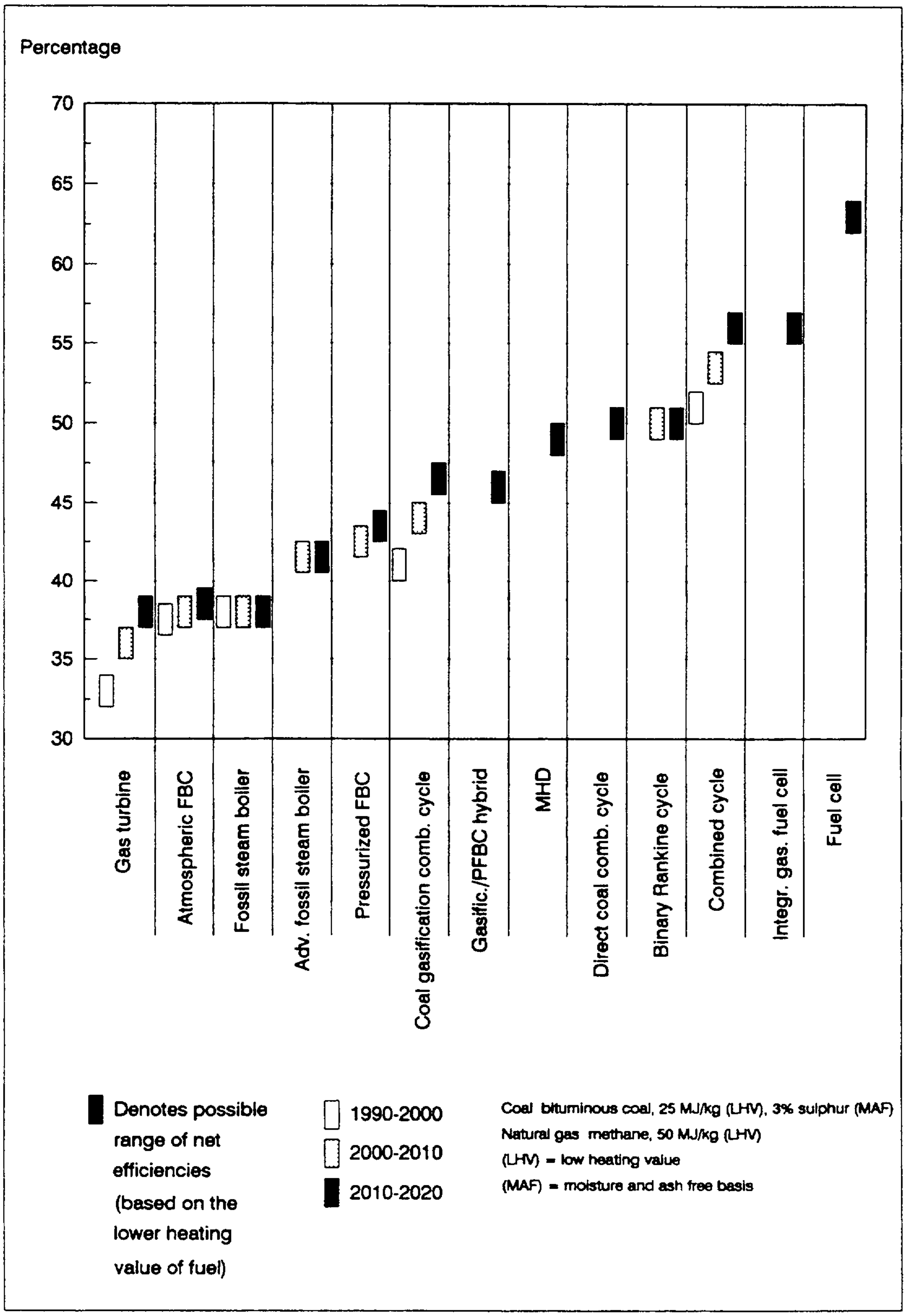

Fig. 12 Overall thermal efficiency.

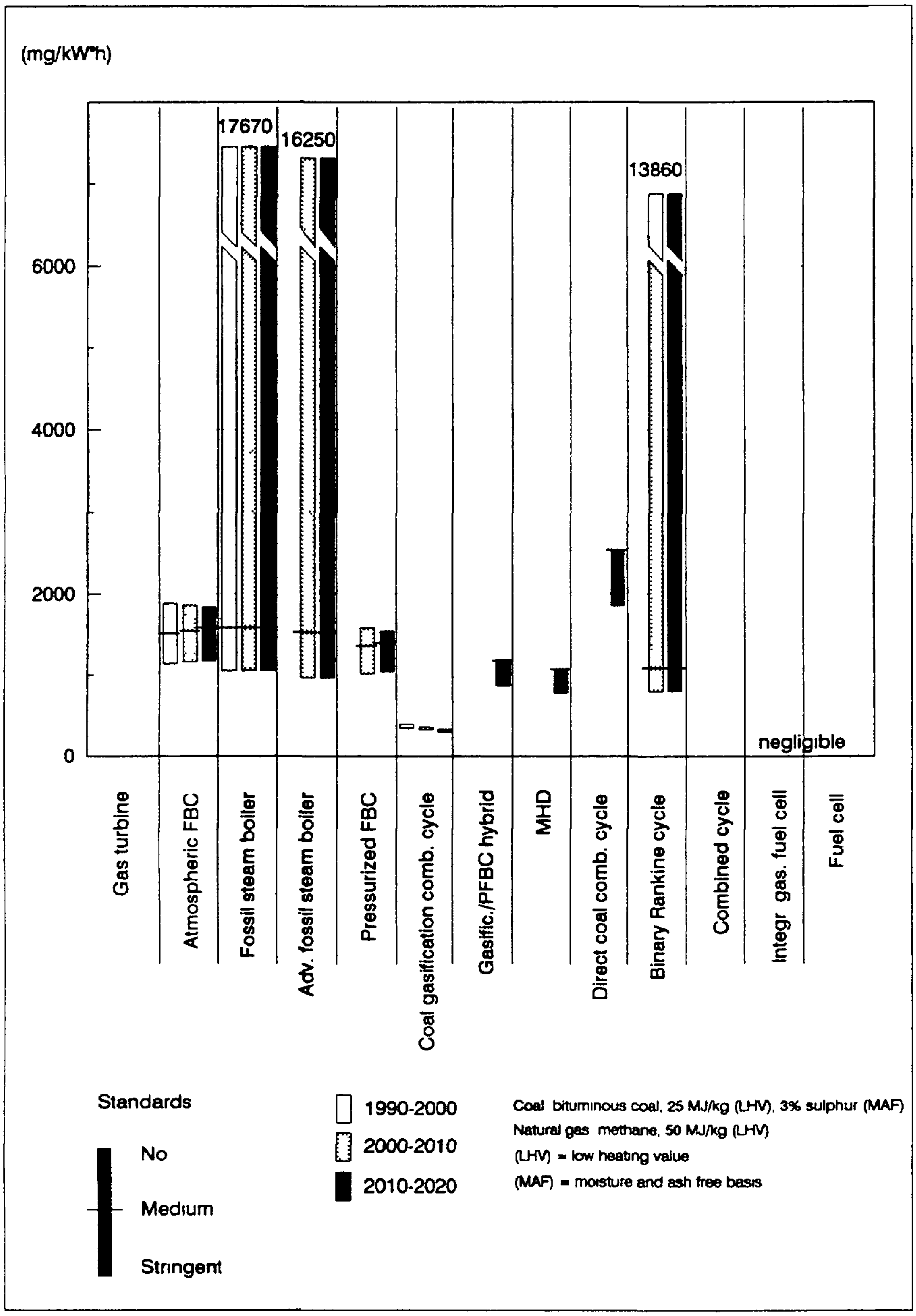

Fig. 13 Sulphur dioxide emissions.

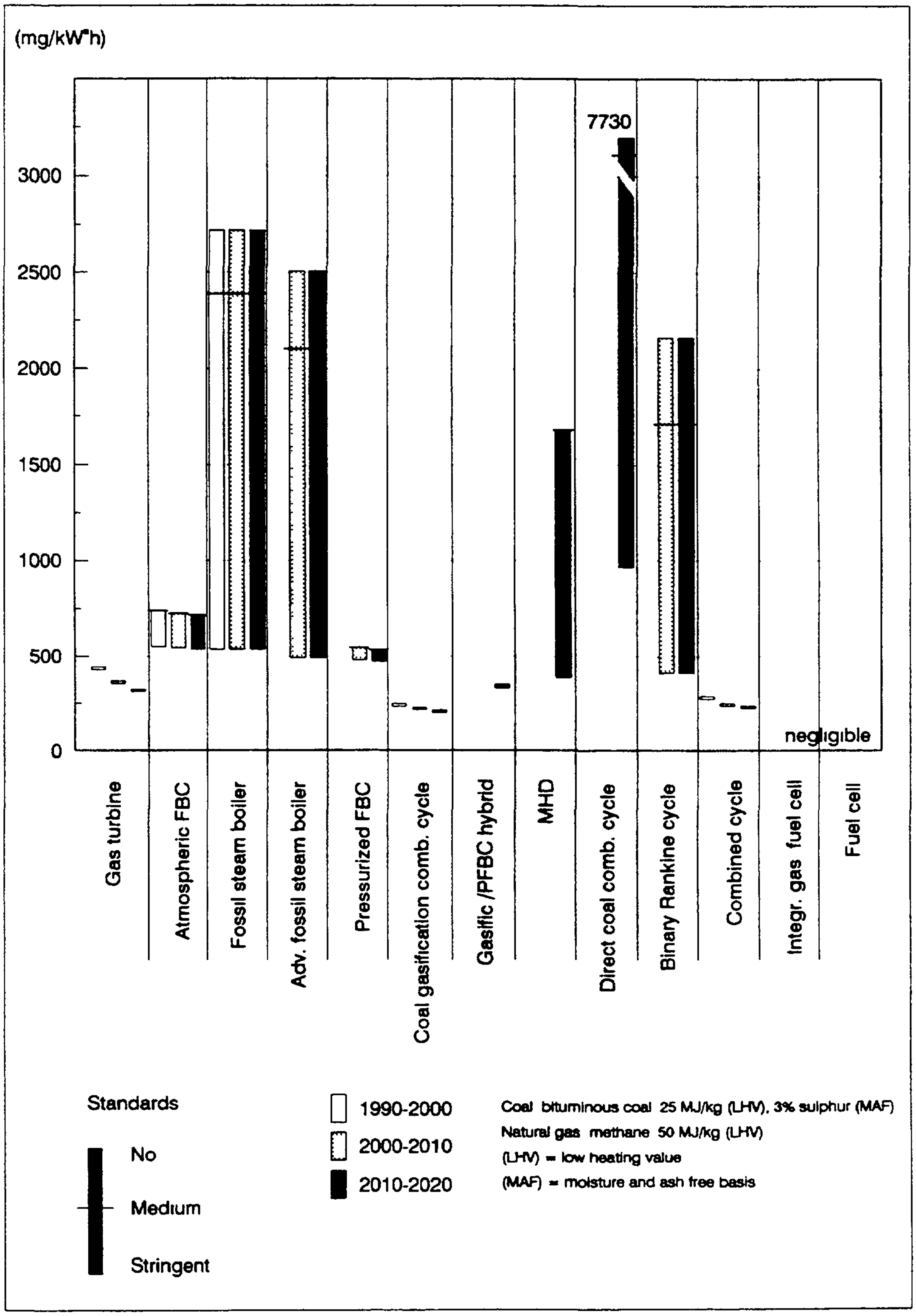

Fig. 14 Nitrogen oxide emissions.

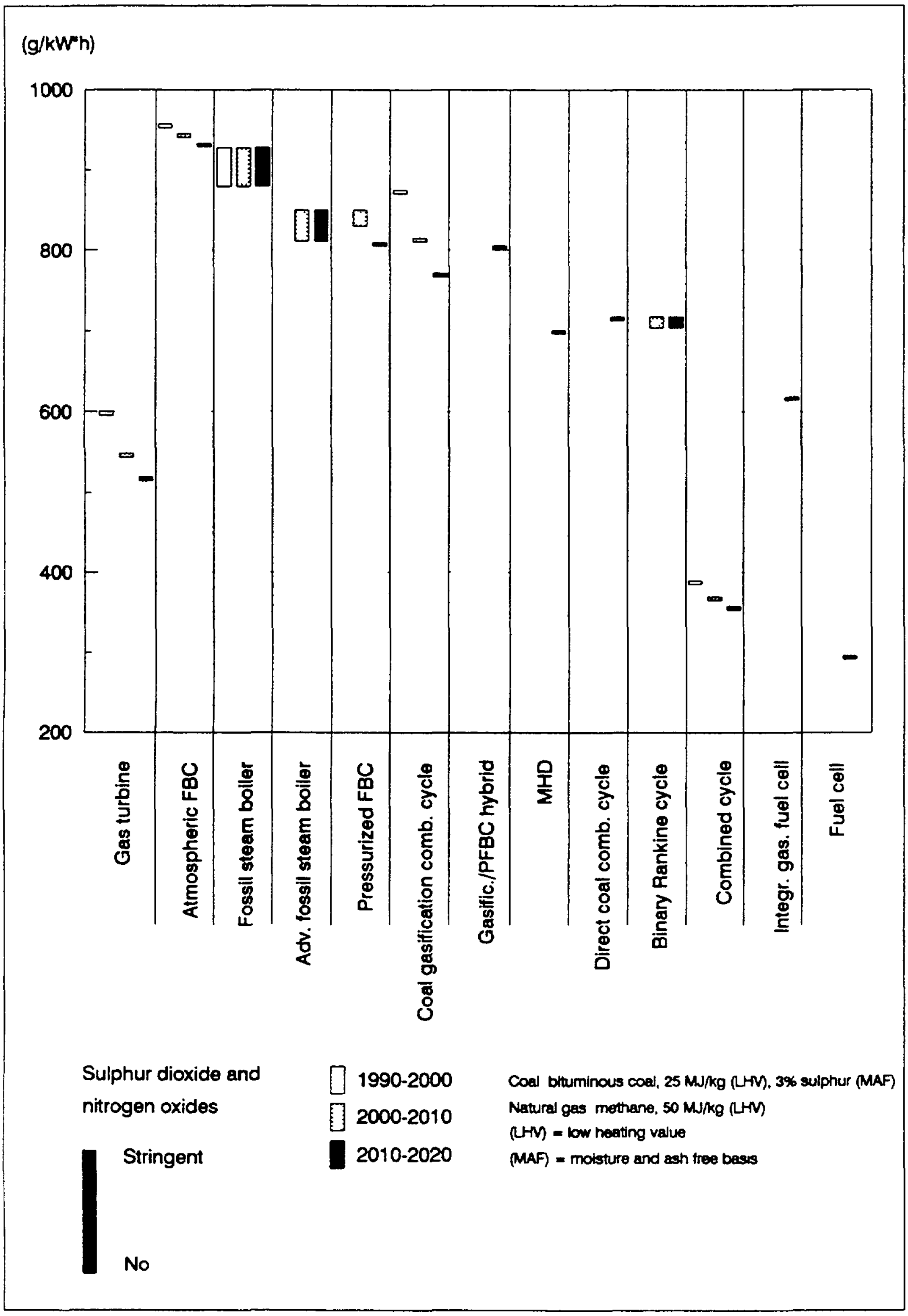

Fig. 15 Carbon dioxide emissions.

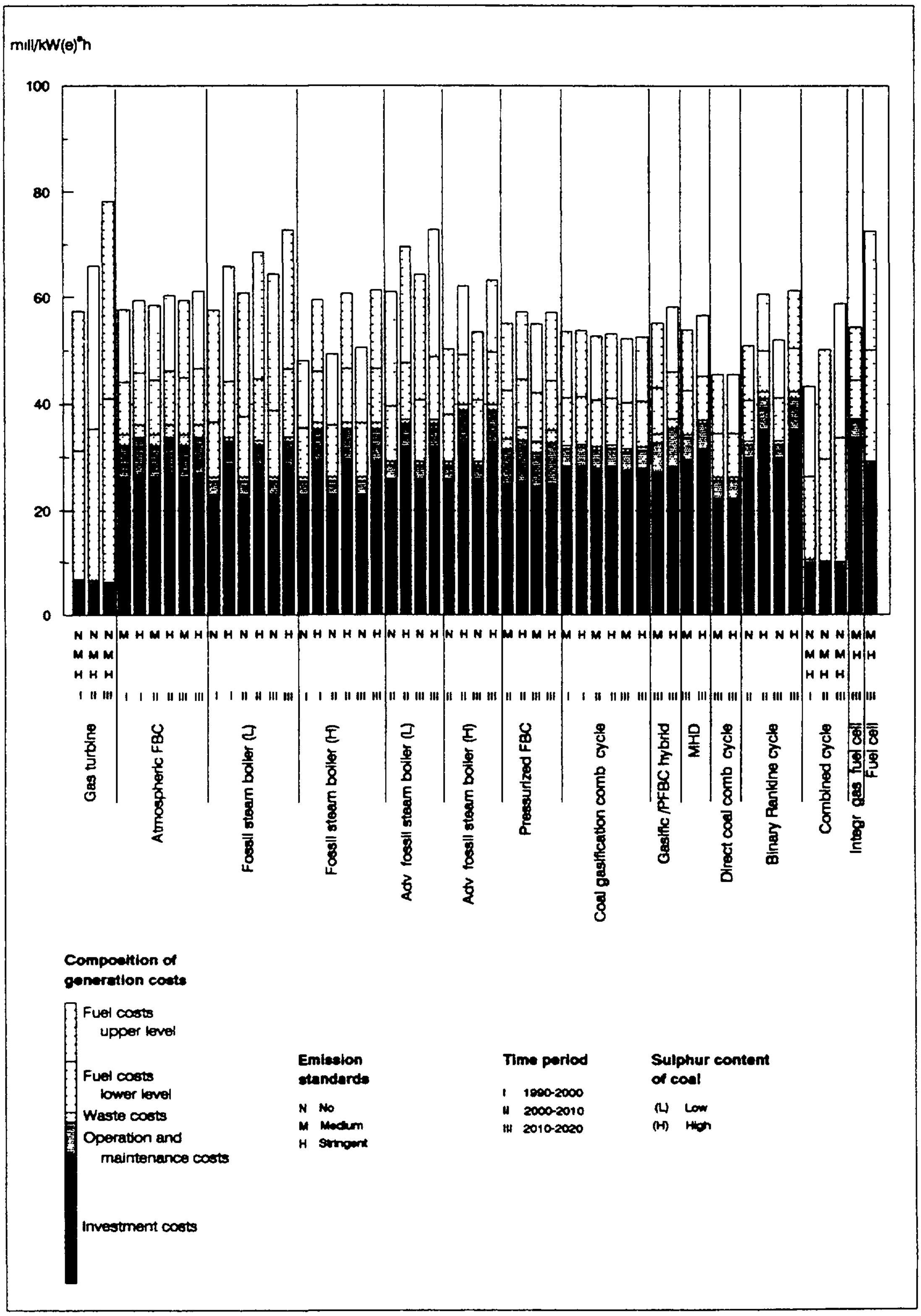

Fig. 16 Comparative assessment of total electricity costs.

ELECTRICITY GENERATION FROM BIOMASS

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ABSTRACT: The term 'biomass energy' refers to the use of plants and wastes from the agricultural or forest product industries to produce heat by direct combustion or fuels using biological or thermochemical conversion technologies. These can generate a wide range of solid, liquid and gaseous fuels which may be used to drive turbines or internal or external combustion engines. Electricity can be generated from biomass using steam turbines or reciprocating engines driving conventional generators as well as by fuel cells.

Large scale (MW) power plant using residues (bagasse, shells, wood waste and black liquors) through combustion, steam generation and turbines is well established. At present, use of purpose grown biomass is restricted to fuel alcohol programmes and some fuel wood plantations. Technical developments have been aimed at increasing efficiencies and decreasing environmental impact of large combustion systems as well as extending the range of conversion techniques used to upgrade low energy-density, diffuse resource to a higher energy fuel in order to reduce transport costs, improve efficiency, reduce negative environmental impacts and increase the feasibility of using biomass to drive smaller generators using reciprocating engines for local power generation at the kW scale.

The environmental impacts of such systems may be negative if adequate controls are not enforced. Traditional use of biomass for energy has been associated with deforestation, erosion and desertification; these problems can be avoided by proper management. Most conversion and end-use processes will produce emissions and effluents containing potentially harmful substances. However, these can be reduced, removed or contained by suitable design; but at a cost which may reduce the feasibility of such use since the economics of biomass based electricity systems are dependent on competing uses of the resource base, the price of alternative fuels, costs of waste treatment and capital costs.

[1] ETSU would like to acknowledge the assistance given by Dr. Jim Coombs of CPL Scientific Ltd. in the preparation of this paper.

1. INTRODUCTION

The term biomass is used here to describe raw materials of biological (mainly plant) origin derived from purpose grown (energy) crops or as wastes, residues and by-products from forestry, agriculture and food industries. Historically biomass, largely as wood and farm wastes and residues, was used as a combustion fuel on a global basis. For instance in 1850 over 90% of energy consumed in the USA was derived from wood. Over the last century coal, oil and natural gas have increasingly replaced biomass as commercial fuels in developed countries. Although, for a high proportion of the world's population, in rural regions of the less developed nations biomass remains the major source of energy. On average in the developed countries biomass energy contributes less than 3% of around 187 GJ per capita per annum energy use whilst in the less developed countries it may represent over 40% of an annual per capita use of around 17 GJ.

Biomass is a regenerable energy source dependent on solar energy. Through the process of photosynthesis in plants carbon dioxide is reduced to a stable organic form, as plant material, from which energy can be recovered as work or heat by oxidation with regeneration of the carbon dioxide. The amount of energy available depends first on the yield of plant material and then on the efficiency with which energy is recovered in a usable form from the raw material. The problems with biomass as an energy source are associated with the diffuse and seasonal nature of the resource, the low physical and energy densities and its high moisture content and often rapid biodegradation on storage. As a result considerable energy has to be expended in harvesting, transport, preservation (drying) and upgrading before it can be used for power generation. The costs associated with these procedures makes it difficult for purpose grown biomass to compete with fossil fuels in a free economy at present prices. On the other hand the use of residues and by-products can be economic where energy is recovered in association with anti-pollution measures. In rural economies or countries where foreign exchange problems limit the ability to purchase oil, small scale generation from biomass can be a viable alternative to the use of other renewables such as wind and hydro power.

The economic viability of any biomass power generation scheme is sensitive to legislative manipulation. In developed countries increasing high agricultural productivities linked to low population growth rates and heavy dependence on fossil fuels have led to surpluses, set-aside of land and increasing areas of managed forest plantations. This has encouraged the continuing development of large biomass energy projects aimed at reducing the costs of agricultural surpluses, improving rural incomes, finding new uses for surplus land and decreasing fossil fuel derived green house gasses. In contrast in developing countries the needs are for low cost energy for a rapidly growing population requiring more land to be diverted to food production making biomass fuels harder to come by in many rural regions. The background social and economic picture in various regions of the world are thus so different that the current use of biomass for electricity generation has to be considered on a regional, or even case by case basis, rather than in global terms.

Over the last 20 years or so a series of events linked to rising oil prices followed by a fall, increased agricultural productivity as a result of increased chemical inputs and now growing environmental concern has led to wide fluctuations in the level of government funding and related research programmes. This in turn has led to an unsettled academic or research community as well as disjointed commercial development. This unstable political climate has led to exaggerated claims from basic studies on the one hand and industries rushing to commercialize unproven technology on the other. Many areas of promise remain unfulfilled, whilst in many sectors the industry has stuttered forward in a series of starts and stops with many participants, high rates of insolvency and a limited number of continuing success stories. At the same time the avid promotion of RD&D in the USA and Europe in particular [1, 2] as well as many international initiatives aimed at the developing countries or rural areas [3] and national activities in developing countries [4, 5] has led to an extraordinary wide range of investigations into biomass production as well as development of commercial equipment and processes for conversion and end use at all scales of operation from a few kW to tens of MW [6, 7, 8, 9]. This review presents an overview of this extremely wide range of activities, details technology and attempts to identify the main factors which will influence the development of biomass based electricity generation in future in competition with other renewables [10].

2. RESOURCES AND RESERVES

Biomass production depends on the conversion of solar energy into organic compounds in the process of photo synthesis. The amount of energy trapped reflects the incident solar radiation, the efficiency with which it is trapped and the length of time over which the plant grows. Plant growth will be affected by environmental and nutritional factors as well as by the impact of disease, pests and grazing animals as well as human harvest and use. In many areas of the world the incident radiation is around 5 kWh per square meter per day. The assimilation, conversion and partitioning of fixed carbon in plant growth produces raw materials in yields of between 3 and 25 tonnes dry matter (dm) equivalent per hectare per year (t/ha/y). Most biomass is predominantly woody (comprised of lignocellulose a complex of lignin, cellulose and hemicellulose in approximately equal proportions), moist (with water content, even when air dried, of at least 15% and possibly as high as 98% water). In general biomass has a low ash content of around 1-3% although ash contents of up to 30% occur in some materials. Species which have been selected for food or other industrial use on the basis of high content of sugar, starch, inulin, vegetable oil, hydrocarbons or latex may also be used preferentially to produce higher value fuels. However, since most such plants have been selectively bred for other purposes their use as an energy source is in competition with use as food, animal feed, chemicals or structural materials. The forest industries as well as agricultural and the food processing industries generate large quantities of wastes, residues and by-products; largely composed of lignocellulose or as dilute aqueous effluents. Manures generated from animal feedlots also contain significant levels of both soluble materials and lignocellulosic residues which can also serve as raw materials for production of higher grade fuels.

The availability of these materials can be considered on a global, national, regional or local basis. Factors which affect the potential of plants as solar collectors [11] and plant productivity [12] are well understood and can be used to model the accumulation of biomass on a species, habitat, regional or global basis. As discussed below global estimates are subject to considerable inaccuracy, although of increasing importance not only from the standpoint of energy, but also in relation to recycling of atmospheric carbon dioxide. Attempts to improve the reliability of data by adoption of standard methodology have been supported by UNEP [13] amongst others. A full understanding of the resource base depends on knowledge of both the climatic factors to which plants are subjected and the detailed mechanisms which affect the efficiency with which the physical resources of sun, land, water, carbon dioxide and mineral nutrients are used.

As far as biomass energy production is concerned the most useful measure of productivity is the yield expressed in terms of ash-free dry weight of organic material produced over a given area in a fixed time. For convenience such yields may be expressed in tonnes dry weight of harvestable biomass per hectare and year (t/ha/y). The energy content of this material can easily be calculated since the higher heating value (HHV) of dry ash-free biomass is fairly constant at between 18 and 20 GJ/t. The potential energy yield (product of weight yield and energy content) thus lies between 25 and 500 GJ per ha per year. The wide variation in these extremes reflects the range of global climatic and geographical conditions under which energy crops may be grown.

2.1 Physical Resources

The concept that net primary production reflects dry matter production through photosynthesis and is dependent on the solar energy incident on a given land area, modulated by environmental factors, can be used with sufficient accuracy for global modelling. In such global modelling it is assumed that net primary productivity (NPP) reflects the activity of plant species or ecosystems which have evolved to fit the local climatic conditions which include annual incident radiation, temperature, rainfall, length of growing season, level of soil nutrients and evapotranspiration (water loss). Actual NPP may fall well below the theoretical potential due to the ravages of pests and disease. Estimates of global NPP are shown in Fig. 1 from Esser and Lieth [9]. These authors estimate a global NPP of around 7.4×10^{10} tonnes/year dry matter, with a maximum annual average productivity of around 20 t/ha/y. Short term productivities in selected crops may be in the order of 80 t/ha/y [12, 13]. Considerable uncertainties are associated with most global models, predictions and many claims for yields. These include a lack of global climate data and the difficulties in defining actual periods of vegetation growth over the greater proportion of the earth coupled with problems of accurate sampling, avoiding edge effects for example, from small plots. In general natural yields can be increased by man through inputs in terms of mechanical energy, water (irrigation), plant protection chemicals, the use of controlled environments and so on. Each input has an energy cost and a financial cost which will influence the extent to which such inputs make economic sense for an energy crop.

2.2 Photosynthetic efficiency

Basic studies of the photosynthetic process enables estimates to be made of the upper limits to current productivity as well as offering the future hope of being able to improve NPP [11]. Such improvements may in future be achieved through either conventional breeding or using techniques of recombinant DNA (genetic engineering). So far attempts to improve productivity by modification of plant size and shape as well as improved disease resistance have been successful in many crops ranging from the dwarf grains (wheat, rice) to fast growing clones of Eucalyptus. Attempts to modify photosynthesis have been less successful, although the process is now well understood. Light absorption by the leaf pigments (chlorophyll) results in a charge separation across a membrane which is used to power the splitting of water generating a reductant (NADPH) and energy source (ATP) and oxygen as a waste product. The products of these light dependent membrane associated reactions are used to power the fixation of atmospheric carbon dioxide into carbohydrate, which is then stored as sugar or starch, used for growth or converted into other plant products (lignocellulose, protein, vegetable oils, latex and so on). Energy for growth and conversion is provided by dark respiration, which uses oxygen and releases carbon dioxide. Carbon dioxide is also produced, linked to oxygen consumption, in a light dependent process known as photorespiration which increases in magnitude at higher temperatures and light intensities and at lower carbon dioxide concentrations and higher oxygen concentrations. Photorespiration is seen in most temperate plants. However, a number of species (including the economically important grasses such as sugar cane, maize and sorghum) have an additional metabolic process (the C4 cycle) which functions to pump carbon dioxide into the leaves, reducing photorespiration and increasing yields. Attempts to increase productivity by increasing the level of components of the light reactions of photosynthesis as well as by modification of enzymes of carbon fixation so far provided extensive information but few practical results.

2.3 Biomass Sources

Biomass resource consists of natural vegetation (on land and in water) and the products of managed forestry and agriculture. The greatest mass of biomass is produced in the tropical rain forests (around 64.4 x 10^9 t/y) which is about twice that formed in the oceans (35 x 10^9 t/y). The use of forest biomass can be divided into three areas. Harvesting of natural forest, use of residues from forests or woodland managed for production of timber, paper pulp or other forest products and the specific management of forests for energy through short rotation or coppice systems utilizing fast growing species. The use of agricultural biomass may also be divided into systems which utilize wastes and by-products and those based on purpose grown crops. At present most biomass used for energy purposes comes from harvesting of natural vegetation and the use of wastes and residues. Considerable research has been carried out on energy forests (reflecting the high productivity of such systems [14] and numerous demonstration projects have been initiated with some commercial activity [1, 2, 7, 8, 9, 15, 16]. Agricultural crops are used in the major alcohol programmes as indicated above and breeding of specific varieties for use as fuel in electricity generation has been extensively investigated [17]. Elsewhere the economics has been questioned [18, 19], whilst most systems involving algae and aquatic plants remain experimental [20, 21, 22] although water hyacinth [23] and algal blooms resulting from eutrophication of lakes and inland seas have been harvested and utilized for biogas production [2, 7].

2.4 Forests and Trees

Whole trees may become available during land clearance for a range of purposes; road building, settlement or agriculture. In conventional forestry management and harvesting provides a wide range of by- products suitable for collection and use as an energy source. These include thinnings, branches and tops as well as unsound or diseased trees derived from harvesting of mature stands and stumps obtained during ground clearance for replanting. Further processing in saw mills and factories generate bark, sawdust and off-cuts whilst the pulp industries generate both solid and liquid wastes. On a global basis the energy potential of these wastes and by-products is considerable, but limited by established practices as well as economics of collection and use in competition with alternatives.

The largest forest areas of a global total of around 2.5 x 10^9 ha remain in the USSR, South America, North America, Asian and Pacific region. However, all regions with the exception of Europe are expected to decline by the year 2000, with the greatest rates of loss in Asia, followed by Africa and Latin America, reflecting continuing destruction of the rain forests where the most useful, valuable and widest range of timber trees are found and needs for fuel wood are greatest. Whilst forests in Europe are increasing quite often this reflects replacement of natural mixed deciduous forests by conifers. Similar managed plantations of Eucalyptus have been established in Australia. Increased destruction as well as new planting reflects changes in wood use on a global basis, although use for fuel remains the major use (over 60% of all uses), followed by sawnwood and veneer logs with use for particle board rising rapidly. This last use is significant from the energy point of view since it represents a competitive market for chips, offcuts and sawdust. These by-products are produced in large quantities during conventional sawn timber production. The in-field yield of sawn logs is around 60-90% of the tree volume for softwood and 40-70% for hardwood leaving a large amount of low density trimmings.

The amount of waste from saw mills depends on the kind of log, final product and processing machinery. Sawmill wastes from softwood logs may result in wastes of (in percent of log volume): 6% bark, 8% sawdust and 16% odd wood pieces. Hardwood logs may produce higher amounts of mill wastes: bark 10%, sawdust 10%, pieces 30%. However, this waste may be an important raw material for particle board and pulp, whilst bark may be used for composting. Wastes from plywood manufacture is less. However, planning and blocking of sawn timber can generate up to 30% by volume of further waste, much of which is used as fuel. Both particle board mills and chip mills will use waste as fuel in-house. Considerable amounts of waste wood can be generated as by-products of laminated and particle board based furniture (such as kitchen units) as they are cut from standard size boards.

Large conventional forest fuel wood plantations have been developed in Brazil and the Philippines and smaller plantations exist in many developing countries. In the developed countries (USA and Europe in particular) extensive research has been carried out in order to assess the potential of forest energy systems with a number of alternatives under consideration. These include Short Rotation Intensive Culture (SRIC) or coppicing using intensive agronomic practices including fertilization, herbicides, close spacings and short rotations with fast growing species grown in monoculture. Species which have been considered include varieties of poplar, willow and eucalyptus as well as Leucaena, Robinia, Platanus and Prosopsis, most of which will give realistic dry matter yields of between 5 and 25 t/ha/y with higher values up to 40 t/ha/y in sub-tropic and tropical regions.

2.5 Agriculture and Crops

Most of the worlds food comes from a surprisingly short list of plants, dominated by cereals, root crops and pulses (peas and beans) with high contents of starch, sugar, protein and oil. These include wheat, rice, maize, barley, potatoes, yams and soya many of which also yield fibrous residues (straws or bagasse), often with a low moisture content and high lignocellulose content. Variety in the diet and additional nutrients (minerals and vitamins) are provided by green vegetables and fruit, which produce wastes of higher moisture content as well as dry shells and stones. At present interest in agriculture as a source of biomass energy includes: 1. the use of residues from existing crops (mainly straws from grains and bagasse from cane) produced for food , animal feed or fibre; 2. the growth of existing food crops as a source of sugar for fermentation; 3. the development of new annual crops (sweet sorghum, artichoke, chicory, C4 grass species) and 4. the use of manures derived from animal husbandry (cattle, pigs, chickens).

The exact volumes of residues and manures available are difficult to assess. It has been suggested that arable residues are generally underestimated whilst manures are generally overestimated. For example for the USA estimates of total annual residues generated have varied from around 95 to over 450 x 10^6 t dry weight, with estimates of available residues ranging from 71 to 190 x 10^6 t. It is assumed by some authors that all residues are collectible and only price will determine how much is collected. However, in reality only part will be collectible because of concern for soil erosion and long-term soil productivity and the method of processing. In practice the most likely residues are straws from corn, small grains, sorghum, rice, sugar cane and artichoke.

The composition of manure and amount produced by various species is fairly well known as is herd size in various countries. Annual dry weight of manure produced per head range from a few kilos for poultry to around 1 t for beef cattle. However, if expressed as wet weight of manure per tonne of animal body weight values of between 40 and 80 kg per day are obtained. What is more significant is the way in which the animals such as dairy or beef cattle, swine, sheep, layer hens, broilers, rabbits and turkeys, are housed and manure is managed. Although manure can be collected from the field for small systems in developed countries the more intensive the system the easier it is to collect the manure and at the same time it becomes more essential to treat the manure as an anti-pollution measure. Other factors affecting the energy content of the material includes the amount and type of bedding used, whilst the moisture content will reflect the amount of water used in removing the manure and/or cleaning the buildings. Management depends on four subsystems; collection, processing, storage and transport. Collection is generally mechanical whilst processing in lagoons, screening, aeration, mounds, or in concrete or other types of structures.

A wide range of agro-food and natural product industries produce significant volumes of organic wastes from which energy may be recovered. These include the sugar and starch industries, the production of vegetable oils, fish and meat processing, preservation of fruit and vegetables, the production of beers, wines and spirits by fermentation, manufacture of natural fibre products (cotton, linen, sisal) and so on. The best documented industry is that producing cane sugar where most factories use the fibrous fraction (bagasse) for heat and power generation [24].

The largest biomass fuel programmes are based on C4 grasses; sugar cane in Brazil and Zimbabwe and maize and sorghum in the USA. Other starch crops which have been considered as energy crops include cassava, sago, potatoes and small grains, including wheat. Sugar beet and sweet sorghum have also been quite widely considered as energy crops as have the inulin containing roots or tubers of chicory and Jerusalem artichoke. Most major vegetable-oil crops have been considered as sources of diesel substitute. These crops would also produce fibrous residues which could be combusted or digested in the same way as similar residues from the same species grown for food or animal feed. Small differences might be bred into the energy species since yield is more important than quality when used for energy. Annual grass crops have been studied as a source of combustion fuel. The most detailed studies are those on high fibre cane, grown with the objective of converting excess sugar processing capacity to dedicated electricity production, based on dry mass yields of over 60 t/ha/y. A related C4 grass (Miscanthus) has been considered in the same way for Europe as have various reeds.

2.6 Mariculture and Aquaculture

About one third of all biomass produced on the earth grows in aquatic environments. Aquatic systems have high productivities, especially in warm climates where the biomass can be harvested on a regular basis for much of the year, since their form ensures high levels of interception of solar radiation whilst their habitat avoids problems of water stress, a major factor in reducing productivity of land plants in hot dry climates. Systems which have been investigated include those based on micro-algae, macro-algae (sea-weeds such as kelp), aquatic higher plants (troublesome weeds such as water hyacinth) and emergent aquatics such as reeds and rushes. Natural microscopic biomass resources represented by phytoplankton may approach around 1×10^9 dry t, with the highest amounts in the north temperate seas, reflecting discharge of nutritive wastes and run-off of phosphate and nitrogen from intensive agricultural areas. Harvesting and use of this material as an energy source may be impracticable. However, larger algae are already widely used as a source of food thickeners and industrial chemicals. The largest species are the giant kelps and ascophyllum used for alginate the with smaller Irish moss used to produce carrageenan. Such natural population can generate up to 25 t/ha/y, whilst laboratory experiments have suggested that algae could generate yields of over 100 t/ha/y in managed systems. These yields are similar to those claimed for micro-algae such as Chlorella and Scenedesmus in artificial systems. However, the macro-algae are easier to harvest. Most algae store carbohydrate or glycerides, an interesting exception is Botryococcus which forms an external capsule of long chain hydrocarbons which can be catalytically cracked to give a gasoline fraction. Yields can be 50% by weight. However, the growth rate of the algae is slow, making commercial production unrealistic at present, although this algae continues to attract research interest.

Marsh plants are of interest since reed bed systems can be used as a means of water purification. In the same way proposals to produce aquatic species in artificial ponds or lakes in arid regions has the advantage of utilizing non-arable land and not requiring salt-free water.

3. CONVERSION TECHNOLOGIES

Typically biomass is a diffuse, moist, low density fuel with an energy value of around 20% of that of oil or coal on a weight basis available in many regions only on a seasonal basis. This causes problems in collection, transport and storage which are compounded by the fact that wet biomass is subject to microbial decay and attack by insects. Apart from loss of heat value this can lead to dangers to health and possibilities of fires due to spontaneous combustion in rotting wet biomass piles. Considerable work has been carried out on collection, transport, storage, densification and upgrading of raw biomass to provide drier, more stable, energy dense fuels suitable for transport and storage, compatible with various engines which can be used as prime movers for electricity generation.

3.1 Harvesting, Preparation and Storage

Energy crops can in general be harvested with machinery adapted from that used in other industries. Forest harvest systems may have to be adapted to enable a greater proportion of the wood to be removed, whilst efficient harvesting of SRIC and coppice may require the design of special harvesters. Use of wastes and residues is facilitated where conventional practice results in accumulation at the site of use as in the case of cane bagasse, nut shells, peels, etc in agro-food factories or animal manures in feedlots. Even when generated on site, problems of conveying and storage remain. Where residues have to be collected from the field these problems are compounded. Infield baling or chipping may be used to increase bulk density and transport may be by rail or road systems. Rail has an advantage where large power stations or agro-industrial complexes are concerned, whilst road transport is more suited to small units, or facilities using a variety of inputs from various sources. The main problems in both cases reflect the volume of biomass needed for a power station of any significant size and the low density (both bulk and energy) of most biomass raw materials. Typical bulk densities of woody materials range from around 160 kg per m^3 for bark, through 300 or so for chips to up to 580 for sawdust. Loose straw may have a bulk density of around 60 kg per m^3 which can be increased to over 120 by baling. These problems can be reduced by adopting physical or chemical conversion processes aimed at increasing energy density and fuel flexibility as discussed below.

3.2 Densification

Both transport and storage costs can be decreased if the bulk density of biomass is increased by mechanical means including binding, baling, pelleting, cubing, briquetting and wafering. These processes may include the use of binders or occur at high temperature resulting in partial degradation or charing. The resulting product ranges from cylindrical pellets of a few mm diameter to large bales of several cubic meters volume. The main limitations to use of such techniques are energy and capital costs.

3.3 Combustion

Direct combustion is not strictly a conversion process as biomass itself is used as fuel. It is the traditional means of generating electricity from biomass through steam generation. Direct combustion is suited to use of both biomass energy crops and wastes with a fairly low moisture and ash content. The design of the grate and boiler will determine the completeness of combustion and efficiency of heat transfer. Improved designs aim to increase energy transfer efficiency and decrease emissions. Other improvements include methods for increasing the calorific value of the fuel by partial drying using flue gas, or other waste heat from factory processes [1, 2, 7, 8, 9, 24, 25]. Devices are available to handle most types of biomass ranging from moist to dry. For some devices and feedstocks it may be necessary to reduce size by chipping or grinding, whilst others may be pelletised or briquetted to increase density and size, to ease handling and reduce transport costs.

Efficient designs are the result of detailed studies of the combustion process in which heat causes devolatilisation producing a combustible gas and a solid char. The heat is derived from both combustion of the gas and oxidation of the char once the fuel has been ignited and depends on controlled addition of further fuel. The efficiency of combustion of the volatiles depends on mixing with air and is affected by the gas-phase flame temperature and by the dwell time of gases at high temperature. Air is usually blown in under the grate aiding char combustion and volatilization, whilst addition of extra air in the gas phase ensures combustion of volatiles and small entrained charparticles. The value of a particulate biomass fuel can be expressed in terms of proximate analysis giving information on volatile matter, fixed carbon and ash content, whilst ultimate analysis (elemental composition of C,H,O,N and S) is required for computation of stoichiometric air-fuel ratio. This information in turn may be used to calculate the higher heating value (HHV) of the fuel and from this coupled to actual air:fuel ratio the adiabatic flame-temperature may be found. If the fuel is wet and it is assumed that the water remains in flue gas as vapour, then a lower heating value (LHV)can be calculated. HHV for most biomass is in the range of 16 to 22 MJ/kg, with LHV at 50% moisture of around 8 MJ/kg. Flame temperatures of around 1100-1500 °C can be reached which, combined with suitable boiler design, can result in transfer of between 65 and 80% of the heat content of combusted biomass to water producing steam at high pressure (4-10 MPa).

Direct combustion of biomass for electricity production is only effective as the primary process in fairly large systems for which a wide variety of grates furnaces, suspension burners, pile burners and fluidised-bed combustors have been designed and used in the forest and food products industries to produce power for their own use (Fig. 2, [7]). However, there is a growing tendency to improve efficiency resulting in ability to export electricity to the local grid. The largest biomass fuelled boilers use grate systems adapted from coal-fired systems. These may be up to 100 MW thermal, producing around 200 tonnes steam per hour. Design considerations including methods of stoking (placing the fuel in the burning hearth in an even manner) and supplying combustion air as well as mechanical conveying of the fuel from store to the boiler. The main development is in the increasing use of fluidised bed combustors as an alternative to grates. These have a high thermal efficiency, can burn a mixture of fuels of varying size and moisture content, produces lower emissions and can have extended retention time, high turbulence and work at a high temperature to reduce formation of polyaromatic hydrocarbons. However, such systems are limited in maximum steam pressure and steam temperature as well as size, below 35 MW thermal.

Industrial combustion is typified by practices in the cane sugar industry [24, 25] where the burning of bagasse for steam generation is standard practice (with world wide generation capacity of over 1000 MW). Co-generation, the sequential generation of electricity followed by use of exhaust steam as a heat source, is common place. In contrast the characteristics of a large wood fired power station can be illustrated by reference to one of the large wood fuelled co-generation plant (50 We) built in the USA [1]. These differ in that many sugar factories use their furnaces as incinerators to get rid of surplus bagasse, whilst the objective in the wood fuelled system is to optimise fuel-use efficiency. A similar aim is now adopted in Hawaii, where the cane sugar industry has adapted itself to optimize electricity for export and now produces over 800×10^6 kWh per year of which 50% are exported to utilities. World-wide the industry crushes some 600 million tonnes of cane each year giving it a potential to produce over 4000 MW of power for export to local grids each year. This would require investment in improved boiler systems.

3.4 Pyrolysis

Pyrolysis is the destructive distillation of biomass in the absence of air [26, 27]. It yields a mixture of products consisting of varying proportions of carbon (charcoal), liquids and gases depending on the feedstock characteristics and the design of the reactor which affects the rate and intensity of heating. The simplest systems are the traditional batch kilns used by charcoal producers and the most sophisticated fluid bed fast (flash) systems. The ratio of char:liquid:oil can be controlled in more sophisticated systems by altering heating rate, residence time of reaction products, highest temperature reached and pressure. Systems aimed at optimization of oil or gas have been run at pilot scale. Gases from the process are low energy, typically 7-10 MJ per m^3. The process is simple, making it amenable to a wide range of feedstocks in small scale systems, which may be transportable.

At present the major pyrolysis product (and indeed the major upgraded biomass based fuel) is charcoal in which the heating value is increased to around 30 GJ/t. World production probably approaches 20 million tonnes per annum of which over 18×10^6 t are produced in developing countries. This can be used in small gasifiers, generating low energy gas suitable for use in spark ignition-engine driven generators in the kW range, Fig. 3. Research and development, within the EC in particular [28] is aimed at improving production of pyrolysis oil as a means of generating a higher energy density product at small local stations, with the oil transported to central power stations in the MW range.

3.5 Gasification

The term covers processes in which biomass is heated in less than the stoichiometric amount of air needed for complete combustion in equipment which results in products which are mainly gas [26, 27]. Three types of process can be distinguished; air gasification, oxygen gasification and hydrogen gasification. These yield low energy gas with a heating value of around 5 MJ per m^3 (producer gas, a mixture of nitrogen, carbon monoxide, carbon dioxide, water vapour, methane and hydrogen), synthesis gas (a mixture of hydrogen and carbon monoxide) and syngas (synthetic natural gas, methane), respectively. The feedstock is usually wood or other dry lignocellulosic residues. A wide range of small scale air-blown gasifiers of updraft, down draft or more complex design, have been built and marketed; mainly producing fuel for engines (transport or electricity generation). Oxygen blown systems, which have been considered for methanol production, and hydrogasifiers planned on a much larger scale, around 1000 tonne/day raw material input, have attracted considerable research interest and some pilot or demonstration facilities have been built: these processes are not commercial at present.

In small batch systems part of the fuel is burnt to produce heat which first evaporates water from the wet biomass and then results in thermal decomposition with the gaseous components reduced by strong endothermic reactions. The main factor affecting gas composition is the water content of the biomass, with producer gas from wet biomass having a higher nitrogen, hydrogen and steam with a lower heating value of around 3 MJ/m^3. In contrast oxygen blown systems using dry biomass can produce gas with heating value in excess of 30 MJ/m^3.

3.6 Catalytic Liquefaction

Heating of dry, finely divided biomass in the presence of metal catalysts or organic materials such as tetralin, can result in the formation of oxy-hydrocarbons of varying carbon chain length and oxygen content. These can be upgraded by catalytic hydro-cracking in processes similar to those used in the petrochemical industry. Two such processes (PERC and LBL) were investigated at pilot scale in the USA and research studies carried out in Europe, Japan and Canada. Similar hydrocarbons can be produced by catalysis starting with synthesis gas. Again the process is similar to that developed for fossil fuel feedstocks. A number of routes to hydrocarbon mixtures, similar to diesel fuel or petroleum spirit (gasoline) from biomass-derived synthesis gas are possible. These include the Fisher-Tropsch (F-T) synthesis and the formation of methanol followed by the use of zeolite catalysts in a polymerisation process. At present the F-T synthesis forms the basis of the South African SASOL process (coal to oil), whilst the methanol route is used in New Zealand starting with natural gas. At present the use of biomass in such processes is restricted to basic research, although some of the partial reactions have been run at pilot scale in the past.

3.7 Anaerobic Digestion

Biogas (a mixture of methane and carbon dioxide) can be produced from any organic material when enclosed in an anaerobic environment (free from oxygen). The process has been widely developed [3, 4, 5, 7, 28, 29, 30] to use a wide range of wet biomass wastes and residues [31, 32] as well as a means of waste treatment [29]. The process has been more widely studied than any other biomass technology [33], reflecting both the range of materials which can be digested and the ease of obtaining results through simple collection of the gas. Yields and gas quality varies widely depending on the nature of the feed, the retention time in the reactor, the solids loading and the reactor design and operating temperature. Locally fabricated digesters can be low cost, whilst second generation systems are effective means of effluent treatment.

A very large number of small digesters have been built and run on manures and plant residues with varying success in developing countries [41]. In developed countries the process which has been used for almost a century for treatment of sewage sludges, was adapted to farm manures in the 1970s and early 1980s. This interest declined as oil prices dropped and current interest is now focussed on high solids digesters optimized for high volumetric gas production or high rate digesters (anaerobic filters, upflow sludge blankets or contact digesters with cell recycle) aimed at rapid treatment of large volumes of dilute effluents from agro-industrial processes. Some large farm based systems are still being developed in Denmark for example whilst anaerobic digestion of aquatic biomass (micro-algae, green algae, kelp or water hyacinth) or purpose grown energy crops is still mainly experimental.

Anaerobic digestion works best with feedstocks of high water content and high content of soluble organic materials of low molecular weight. Hence, the fastest rates of gas production and shortest solids retention times are possible with systems designed to remove BOD from agro-industrial process waste streams, sugar or starch factories, breweries etc. With high dilution rates the systems are designed in such a way that the bacterial flora is retained on a reticulate surface (anaerobic filter), as a sludge blanket (UASB) or recycled after settling (contact digester) (Fig. 4 [9]).

An alternative method of achieving the high volumetric yields required to make AD an economic process as far as energy is concerned is to increase the loading rate to around 8-12 kg of volatile substance per m^3 reactor volume per day, resulting in solids contents of around 30 to 40%, with retention times of around 15 days. Considerable effort has been expended in the study of factors which affect growth of the microbial population on start-up, the stability of systems to sudden increase in organic loading (shock loading), temperature, mineral nutrients, inhibitors and so on. As a result commercial systems are now available capable of reliable operation. The composition and quantity of gas produced varies with the feedstock composition and the digester design, in general around 0.2 to 0.3 m^3 of biogas are produced per kg dry solids. Theoretically biogas should contain equal volumes of methane and carbon dioxide with only trace amounts of other gases. The calorific value is around 25 MJ per m^3. In practice biogas is often enriched for methane as carbon dioxide is preferentially retained in solution, whilst reduction of other elemental components can result in formation of hydrogen sulphide and ammonia. Solid biomass with a high lignocellulose content, such as might be produced from tree-based energy farms or as representative of many agricultural wastes such as straw, are more difficult to digest. Basically, the process of hydrolysis of polymers is followed by acidogenesis (an acid producing step) and the methanogenesis (the methane production step). Rates of gas production can be increased by pretreating the feedstock with acid, alkali or enzymes to increase digestibility. This material may then be digested in a two stage process with acetogenesis separated from methanogenesis. Alternatively the untreated fibrous material may be packed into a suitable container inoculated with both hydrolytic and acetogenic bacteria and percolated with liquid which transports released acids to the second methanogenic stage.

3.8 Fermentation

The fermentation of sugar-rich biomass to alcohol (ethanol) using yeast has been used for beverage production for thousand of years. Fuel ethanol production uses similar technology optimized for quantity rather than quality. This consists of converting the feedstock (sugar, starch, inulin or cellulose rich biomass) to provide a feed stream containing about 15 to 20% fermentable sugar, the fermentation process yielding about 8-10% alcohol in water and recovery of the alcohol (96%) by distillation, which may be followed by dehydration to give pure ethanol. Sugar and starch based systems are commercial, forming the basis of the alcohol fuel programmes in Brazil, the USA, Zimbabwe and elsewhere [1, 4, 7, 8, 9]. Mass yields are around 50% of sugar feedstock. Energy yields are more complex to calculate and estimates have been a subject of controversy. Where energy for the process comes from combustion of the fibrous part of the crop, as with sugar cane, there is a net energy gain. A wide range of novel yeasts, bacteria and fungi capable of producing ethanol from a wider range of raw materials have been identified and investigated. Of these the bacteria Zymomonas mobilise and Clostridium thermocellum have received particular attention and have been used in some pilot studies. A second fermentation, used commercially in the past, is that catalysed by another species of Clostridium (C.acetobutylicum), which yields a mixture of acetone, butanol and ethanol. Considerable research effort has been expended in the USA and France, aimed at improving the process by increasing the yield and increasing the resistance of the bacteria to inhibition by solvent. However, no major break through has yet been achieved.

3.9 Hydrolysis

Considerable research has been devoted to development of acid [34, 35] or enzyme [36] based hydrolysis systems aimed at obtaining fermentable sugars from lignocellulosic wastes and purpose grown wood. At present such plant is limited acid based processes in the USSR, although acid technologies have been used elsewhere in the past. During the 1980s considerable efforts were directed towards research and development of acid based systems and limitations identified as mainly related to engineering requirements and economics. In contrast limitations to enzyme based systems reflect the activity of current enzymes and costs of production. Considerable research activities, with the focus on identification of new organisms and improvement of existing ones using recombinant gene technologies. Pretreatment, based on physical or chemical processes can increase the ease of hydrolysis. Processes which have been investigated include size reduction by milling, use of ultrasonics or radiation, dilute acid or alkali treatment, use of organic solvents, oxidants or metal salts. The effects include decrease in particle size, removal of lignin, decrease in degree of crystalline of lignin, removal of hemicellulose and swelling of the fibrous structure. However, the process which appears of most value on a cost-benefit basis is steam explosion in which the woody material is treated with steam under pressure and then exploded by rapid reduction to atmospheric pressure. Processes are available which operate on either a batch or a continuous basis. Such treatment can result in a 40% increase in sugar yields.

3.10 Extraction

A number of plants species yield products which may be expressed or extracted using solvents and used directly as fuels or converted by esterification or cracking. The main groups are those producing vegetable oils or complex hydrocarbons. As far as vegetable oils are concerned species of potential interest include oil palm, coconut, sunflower, oilseed rape, soybean, maize and groundnut. The oil may be recovered as in the food industry by mechanical extraction using extruders or by solvent extraction. The ease of use in engines may be improved by esterification to form methyl or ethyl esters. In the same way numerous plant species produce complex hydrocarbons; these include Euphorbia lathyris and Parthenium argentatum (guayule) which are adapted to arid regions. The main problems with these plants are sustainable yields, which at present lie in the region of one or two tonne/ha/year.

3.11 Hydrogen Production

Green algae, cyanobacteria (blue-green algae) and photosynthetic bacteria are capable of producing hydrogen from water in a light dependent process. Similar mechanisms have also been investigated in experimental systems using isolated organelles and enzymes from various photosynthetic species or artificial model systems [37]. The mechanism of hydrogen production from water can be divided into two types; hydrogenase catalyzed and nitrogenase catalyzed.Hydrogenase dependent reactions also occur in the photosynthetic bacteria where the electron donors are low MW organic compounds. At present such systems remain at the research level.

3.12 Biomass Fuel Driven Prime Movers

In general steam or gas driven turbines are most suitable for larger power plant in the MW range whilst various types of internal combustion engines based on spark or compression ignition are used for systems up to about 1 MW. These may be coupled to synchronous or asynchronous generators as appropriate. Both types of internal combustion engine may be adapted to the whole range of liquid and gaseous biomass derived fuels by attention to gas clean up to reduce engine damage, modification of ignition and timing, adjustment of air:fuel ratios, alteration of compression ratios and, with some fuels, changes in construction materials. In general electricity will be generated from biomass combustion using steam in a back pressure turbo-alternator. There is a tendency in the agro-food industries to consolidate facilities into fewer larger and more efficient units. As a result large turbine systems have been designed, working at increased operating pressures and steam temperatures with better heat recovery where co-generation is practiced. For instance on the Hawaiian island of Kauai nine low-pressure boilers and three turbo-generators were replaced by one high-pressure boiler servicing a single double-extraction/condensing turbo- generator. These larger turbines are those used in the smaller coal or oil fuelled power stations. However, the possibility of increasing performance through use of steam injected gas turbines linked to an air-blown gasifiers has been investigated in the cane sugar industry. This can increase the potential for exportable electricity from around 200 kWh per tonne of cane (tc) to over 450 kWh/tc. The main problems are associated with gas clean up since particulates and vapour phase components such as potassium oxide, sulphides and chlorides can cause considerable turbine damage. On the smaller scale piston-type steam engines can be used to drive generators. However, these have lower efficiencies and require considerable maintenance, making internal combustion engines using other biomass derived fuels more attractive for smaller power generation systems.

Spark ignition engines may be adapted to run on most gaseous and liquid fuels derived from biomass, including biogas, producer gas, methanol and ethanol as well as catalytically derived oxy-hydrocarbon and petroleum analogues. They are of particular interest for small power generation using biogas [33] or rural situations [38, 39, 40] using alcohols, biogas or producer gas as fuel. Where producer gas is used the main problems lie in gas clean up to prevent engine damage by fly ash, tars and soot. Particulates can be removed by filtration or cyclone separator whilst tars may be removed using water or oil based gas scrubbers, or a combination of systems. Synthesis gas may also be used in spark ignition engines for power generation, with less need for clean up. Biogas needs to have moisture content reduced and may also have to be scrubbed to remove hydrogen sulphide, typically using an iron oxide box system. The heating value can be increased by also removing carbon dioxide, on the small scale using pressurized water scrubbers. With both biogas and producer gas the low heating value of the gas/air mixtures results in a 30-40% derating of the engines which may be overcome to some extent by supercharging.

Vegetable oil based diesel substitutes and products of catalytic liquefaction or catalysis are most suited to compression ignition engines although modification of engine (addition of spark plug) or fuel (addition of chemical igniter or admixture with ordinary diesel oil) can enable such engines to be used with biogas, producer gas or alcohols; ethanol or methanol (duel fuel or gas engines). Extensive experimentation has shown that unmodified vegetable oils can be used in naturally aspirated precombustion chamber engines. However, they cannot be used in direct injection engines without modification to the engine or fuel (transesterification). With producer gas or raw biogas diesel engines show a much smaller derating (around 10%) than spark ignition engines, but they always require addition of small amounts of diesel fuel as igniter.

Novel generating systems include those based on the Stirling and Rankin cycles, as well as high temperature ceramic turbines. These systems are of interest since they potentially at least promise higher efficiencies for smaller generator systems than those achieved using conventional small internal combustion engines. The Stirling cycle involves two processes, constant temperature and constant volume. The heat engine consists of a displacement piston which alternately transfers the working fluid between the high temperature expansion space and the low temperature compression space; a power piston that transmits the change in pressure to a crank, a heat exchanger, regenerator and a cooler. Systems running on rice husks or wood chips have been built, linked to small (kW) power generators. The Rankin cycle engine is a heat engine designed to extract work that operates on the gas- liquid phase change cycle and is capable of high efficiencies. Engines using water as the heat medium have been developed to run on wastes such as rice husks or wood chips with the vapour (steam) passed through a turbine generator of 0.4 to 3 MW using around 1.75 t/h of wood per MW. Ceramic turbines, currently in the experimental phase of development, operating at temperatures in excess of 1500 degree centigrade again offer possibilities of high efficiencies in small generator systems in the kW range.

3.13 Fuel and Bioelectric Cells

Although most electricity is generated from biomass fuels using conventional generators alternative non-mechnical possibilities exist. In a fuel cell the reactants are oxygen and an organic compound, typically hydrogen gas an alcohol or hydrocarbon (methanol, ethanol, methane, etc). The systems may be operated at room temperature or at higher temperatures using molten salts as electrolytes. Stable fuel cells have been run for several thousand hours. Energy efficiencies are around 35%, however, power densities are lower, by a factor of about 10, than conventional generators. In order to increase the rated power of a fuel cell the area of the electrode has to be increased. Hence, there is no scale-up factor, making them a possibility for local small scale power generation. The term bioelectric cell is used to describe a fuel cell in which the organic constituent is continually generated through microbial activity, usually generating hydrogen or methane. Such systems are still experimental.

4. ENVIRONMENTAL IMPACTS

4.1 Biomass Production and Land Use

Over use of biomass as an energy source has been, and in many developing countries continues to be, a major cause of deforestation, soil erosion and desertification. These problems are intensified where soil fertility is further reduced as a consequence of over use of manure and agricultural residues as fuel. Combustion in simple systems generates respirable particulates, polycyclic hydrocarbons and other lower molecular weight organics and carbon monoxide. In some regions there may be conflict in land use between crops for energy and crops for food [41]. However, in the USA and now Europe the main problems are associated with over production of food and the need to take land out of production through set- aside schemes. Here, the production of crops for industrial use is seen as an essential development [42, 43] with research funds of over US $300 million being used to fund 'agro-industrial research' over the next four years. The need for such research reflects the need to establish economic systems capable of sustained output whilst avoiding the problems which have been identified where food crops have been grown in monoculture over large areas with high chemical inputs and with almost total destruction of natural vegetation, hedges, streams and ditches. There is no technical reason why non-polluting conversion systems should not be built to take advantage of the benefits of displacing fossil fuels. On the other hand more information is required concerning the environmental impacts of large biomass energy schemes, especially where they involve the introduction of exotic species. It is possible that substantial changes in land use can alter precipitation and frost patterns. Exactly what would happen as a result of global production of energy crops on a massive scale is not known.

4.2 Atmospheric Carbon Dioxide

The facts that photosynthesis removes atmospheric carbon dioxide by fixation into plant biomass and that most oil, gas and coal reserves represent the products of photosynthesis in the past are well known. Carbon incorporated into the worlds standing biomass would, without mans intervention, tend to reach equilibrium with plant material converted back to carbon dioxide through oxidation by respiration in animals following consumption as food, through microbial decay or as a result of natural forest fires started by lightning. Current destruction of the rain forests as well as increased consumption of fossil fuels has led to the well documented increase in atmospheric carbon dioxide. Replacement of fossil fuels with biomass derived fuels will not decrease the level of carbon dioxide, although establishment of tree-based energy plantations for future use could do this. However, increased use of biomass could, through reduction of dependence on fossil fuels, reduce the rate of increase in level of atmospheric carbon dioxide. At the same time if emissions of other green house gases such as carbon monoxide and methane are not controlled the potential benefits of biomass use could be reduced.

4.3 Residue and Waste Utilization

The environmental impacts of over-utilization of organic wastes lie in loss of soil humus, reduction of fertility, increased erosion and loss of water holding capacity. However, conversely there is a limit to the amount of sludges, manures and fibrous crop residues which can be incorporated into agricultural land management systems. Problems associated with heavy metal loading as well as pollution of water courses by run-off and nuisance caused by odours has resulted in legislation restricting dumping of sewage and industrial sludges to land as well as encouraging management of manure, slurries and effluents from silage clamps in many developed countries. At the same time concern about air pollution, accidents due to heavy smoke banks and fire damage has led to tough controls or bans on in-field straw burning. Hence, straw combusters and anaerobic digesters have positive environmental benefits. In the same way rational removal of waste wood from plantations can reduce fungal disease, improve forest management and reduce air pollution resulting from release of partial-combustion products where trash is burnt in open smouldering piles on site. In general such practices can reduce the accumulation of mineral nutrient (eutrophication) in lakes and rivers and reduce pollution of water resources by nitrates derived from biomass decomposition in the field.

What is required is a balanced policy of management, matching the amounts of biomass left or added to land to specific local needs reflecting soil type, crops cycles, harvesting techniques, climate, precipitation and ground contours. Residues prevent soil detachment and reduce the transport velocity of runoff, each tonne/ha of surface litter can reduce soil erosion by up to 65%, with present rates often approaching 20 tonne/ha/year. Associated with such runoff are sediment and nutrient loads which can have both beneficial and detrimental effects, depending on the site. Runoff can be reduced by adoption of low tillage systems. However, these in turn require increased use of herbicides and other chemicals, which combined with pesticide residues have significant negative environmental effects. A combination of breeding for disease resistance and integrated pest management coupled with energy plantations based on mixed species would help reduce the need for chemical inputs. Use of surplus residues or wastes in controlled combustion or fuel generation systems, where fitted with suitable systems to control effluents and gaseous emissions, can only be of environmental benefit so long as indiscriminate over use of residues is prevented.

Residues associated with biomass use can be used as fertilizer. The ash from wood, straw or bagasse combustion is a valuable source of potash, whilst both liquid and solid digestate from anaerobic processes have value as fertilizer or soil conditioner. The digestion process is also effective in destroying pathogenic microorganisms and eggs of parasitic worms. Crop residues may contain 40% of the nitrogen, 10% of the phosphorous and 80% of the potassium applied as fertilizer. Of this a significant amount may be left in the fields in roots, even if above ground biomass is removed. For forests, with conventional stem only harvesting and nutrients derived from precipitation and microbial activity in the rhizosphere, only calcium may have to be added to maintain a balance between removal and addition. As more of the tree or crop is removed additional inputs are required.

4.4 Gaseous Emissions

Both thermal and biological conversion systems will produce gaseous emissions, although these differ in nature. The airborne emissions from thermal systems, including internal combustion engines, are typified by the products of combustion: particulates (fly ash), hydrocarbons and other organic products of partial combustion and oxides of nitrogen (NO^x). Gasification, pyrolysis and catalytic systems may also produce such products, the extent of which depends on the design of the system. Combustion in a turbine or engine also produces a similar range, although particulate emissions will in general be low as preclean-up systems will have been installed in order to reduce engine damage. All thermal systems will also produce carbon dioxide and to a varying extent, depending on combustion efficiency, carbon monoxide. Most biological systems also produce carbon dioxide, whilst anaerobic digesters produce methane. Where biological derived fuels are used in engines combustion products may differ from those from direct combustion of the biomass, with increased release of aldehydes.

In combustion the formation of particulate emissions is affected by the fuel feed rate, the level of fines, the amount of excess air used and the distribution of the combustion air. Particulates can be reduced by staged combustion (stoichiometric underfed air followed by excess overfire air) and removed by use of multiclones, electrostatic precipitators, dry scrubbers and baghouses, with overall reduction of the particulates (in the range of submicron to 2mm at up to $100g/m^3$ flue gas) by over 99%. NO_x is formed through a thermal route from atmospheric nitrogen at high temperature (1600 C) and from oxidation of organic nitrogen fuel components in a temperature insensitive reaction. Thermal NO_x is a problem in advanced high efficiency systems working with refractory grates and low levels of excess air whilst fuel derived NO_x is common to all biomass depending on nitrogen (protein) levels but is dependent on a high air flow, in a starved air system it may end up as diatomic nitrogen. Since n-compounds are more volatile than c-compounds formation from organic n will be reduced in a starved air system. Hence, levels can be controlled by combustor design to fall in the range of 0.4 to 1.2 kg NO_x per MJ (thermal). Large-scale combustors can be equipped with the best possible pollution control technologies, whilst poorly designed or maintained systems can be the worst polluters. To achieve operation within limits set by environmental regulations may require extensive additional equipment for flue gas treatment. This will include a particle trap (multiclone), heat exchanger to cool flue gas, a wet scrubber to remove particulates, an induced draught fan to send flue gases to the atmosphere, treatment of scrubber water including settling and separation of fine fly-ash particles.

Gas streams from pyrolysis or gasification may contain polyaromatic hydrocarbons, such as fluoranthen, chrysen, phenanthrene, benzanthracene, pyrene and benzopyrene. However, these products should be destroyed by combustion where the gases are used either in steam boilers or internal combustion engines. Again control devices can be used in large systems with most problems arising with small poor designs used in developing countries.

With anaerobic digestion the main problems arise from generation of toxic hydrogen sulphide. Gaseous emissions from digesters, distilleries and thermal conversion plant often smell. Low levels of odour may be unavoidable although in general smells can be reduced by good house keeping following good initial design. At the local level product gases from most conversion and end use systems (carbon monoxide, carbon dioxide, hydrogen sulphide, methane, hydrogen, etc) can be lethal to humans or animal life and contribute to explosive mixtures when contained in restricted spaces. Adequate ventilation, proper fluesystems, maintenance to avoid leaks and good plant and building design as well as established safety procedures are essential to avoid injury or death.

4.5 Liquid Effluents

The use of catch crops, increased planting of stands of trees as breaks between fields used for fuel production, the increased use of reed beds and harvesting of algal blooms and water weeds are all factors which can contribute to a reduction in nitrogen content of water run-off or leached into water courses. Of more significance are the liquid effluents from fermentation, anaerobic digestion, pyrolysis and gasification as well as electricity generation itself. Sources of liquid include wash waters, condensates, tower blown down, stillage, digestate and pyroligneous liquor as well as oil fractions and contaminated water from gas scrubbers. Various treatments are technically possible to deal with such liquids, the main problem is cost. Probably the most toxic product is the carcinogenic liquid fraction from pyrolysis plants. However, in large scale plants liquids can be injected back into the system, or pass into the boiler flame and be combusted after concentration. They may also be treated by aerobic biological systems. Again the main problems are associated with small scale rural systems where proper disposal of liquid fractions remains a serious problem.

4.6 Solid Wastes

The main solid waste produced from biomass generation systems is fuel ash. Other solids may include feedstock rejects, bagasse, grain dust, soil and stones, waste water sludges and digestate or stillage solids. As with gaseous and liquid wastes these may be treated, or disposed off as fertilizer, back to land. The techniques exist, the needs are for legislation to enforce environmentally sound practice, where economic considerations may discourage adequate treatment.

4.7 Prime Movers

The main environmental concerns as far as actual power generation is concerned relate to gaseous emissions, thermal pollution from cooling water and noise. The potential gaseous emissions are similar to those for direct combustion, although additional products may be formed reflecting the chemical composition of the fuel (eg aldehydes from alcohols). In general emissions are easier to control by tuning the engine and adjusting air:fuel ratios and fitting of catalytic converters. Once again the extent to which this is done will reflect a combination of legislation, economics and participation of the user. Large quantities of cooling water may pose problems where co-generation is not practiced. Solid wastes are not a problem. On the other hand most prime movers are noisy. Impact can be reduced by housing generation plant in suitable buildings, with the generators below ground level. Reduction in noise and vibration associated with transport, handling, milling and conveying biomass is more difficult and local noise is probably unavoidable. When used as diesel substitutes vegetable oil based fuels show gas phase emissions which are similar to diesel oil, but have higher levels of NO_x but lower smoke levels. However, the esters show significantly increased levels of aldehydes, similar to those encountered with alcohol fuels.

4.8 Visual Impact

Large biomass plantations will affect the look of the landscape, whilst large power generating stations may cover several ha with large buildings, stacks, conveyors and silos or piles of raw materials. Planting mixed systems to contour lines can preserve landscape features. However, their is little which can be done to disguise the visual impact of a large factory complex. Small generating systems can be housed in attractive buildings, designed to reduce noise and other environmental impacts. However, all too often, especially in developing countries, such facilities may rapidly deteriorate, becoming an eyesore which general tidying and a coat of paint could soon remedy. As with most systems it is a case of thought, environmental impact analysis, planning, regulatory compliance, economics and human interest which tips the balance between an environmentally sound facility and an environmentally damaging system. This balance can be shifted by education, enforcement and government incentives.

5. ECONOMICS OF ELECTRICITY GENERATION

In spite of the very large volume of data published on biomass energy production and conversion proper economic analysis of many systems is lacking. Available data, in order of frequency, is obtained as an educated guess (made up), derived from models or derived from working experience. This order reflects the lack of hard data from operating facilities as well as the concentration of many researchers on basic reactions and process design. Typical conclusions are those reported in a survey of the end use of biogas in Europe [33]; that 'profitability data are rare and difficult to obtain'. In discussion the potential of large biomass energy plantations in Europe it was concluded [28] that 'the depth and scope will depend on the future supply price of biomass and the cost of conversion technologies. The future costs of biomass are very difficult to evaluate. Data is available but does not reflect the future situation of a well developed bio-energy market'.

Here, estimates are presented along with a few examples from actual operating experience. Due to the wide variation in moisture content and conversion efficiencies of various biomass fuels and processes economic data is only really of value if expressed in terms of dry weight, energy content or final price of a unit of electricity. Again, such information may not be readily available as raw materials may not be properly described and conversion efficiencies calculated in many reports.

5.1 Raw Materials

The energy content of the resource is fairly constant if expressed in terms of dry weight of combustible (volatile) organic matter. This reflects the common high carbohydrate content of most plant materials giving a value of around 18 GJ per tonne, which is reduced as a result of moisture and ash content. In combustion the first law boiler efficiency is determined by fuel moisture, whilst flame temperature is determined by levels of excess air. Many wastes and residues, as well as purpose grown biomass, may have a moisture content of around 50% lowering the calorific value to around 8 GJ per tonne. This may be increased by sun (air) drying as in the case of straw or by recirculation of process waste heat, as with bagasse in some sugar factories. Conversion to liquid fuel increases energy content and combustion efficiency as well as reducing particulate emissions. For instance fermentation to ethanol increases the CV to 28 GJ per tonne, although this is still low compared with 46 GJ per tonne for petroleum. Raw material costs vary over a very wide range; from negative values associated with disposal to around US $10-15 per t for collected straw or wood wastes and up to US $150 per tonne for sugar or starch crops, depending on local agricultural policies and currency exchange rates. The economics of biomass derived electricity generation are complex due to the interaction of simple costs of biomass production, transport, processing, conversion and end use interacting with partial processes of other systems. Production costs reflect land values, which in turn are influenced by opportunity costs reflecting food production and agricultural subsidies, surpluses and set aside schemes. In the same way processes which utilize wastes and residues or produce a by-product which has added value, for instance as a protein supplement in animal feed, may effectively use feed of low or even negative cost. Production costs and yields increase with inputs, whilst transport costs increase with the size of a processing facility.

Since much of the cost of purpose grown biomass lies in establishing the crop final price decreases as yields increase. A detailed assessment which covered most developed countries concluded that at yields of 12 t/ha/y oven dry wood over a 4 year cycle SRIC would generate fuel at a cost of between US $30 and US $100 at the factory gate [15], depending on the level of inputs (fertilizer and irrigation water). These figures are consistent with a Swedish computer model, which indicated that to beat the current market wood price of around US $15 per dry t would require yields of around 10-12 dry t/ha for small plantations and around 20 dry t/ha for large plantations, reflecting higher transport costs [16].

5.2 Conversion Costs

Numerous wood based power systems have been built around the world with the largest in North America where five or more of between 30 and 50 MW capacity have been built in the last decade. On a global basis generation from biomass wastes probably exceeds several GW. Stationary units driven by internal combustion engines are generally economic up to around 1 MW. Engines are readily available for use with biogas or producer gas. Numerous engineering construction and design companies, university groups and extension services have facilitated building of thousands of anaerobic digestion systems around the world. However, most of these are used to generate heat or light, not power. Most work on power production has been carried out in developed countries, especially associated with treatment of sewage, farm manures and agro-industrial effluents. Small gasifier/engine systems have been marketed by various companies based in the Philippines, Brazil, Sweden, Germany, France, Belgium, Netherlands and the USA. These range in size from 10 to 2000 kW. Larger systems of up to 50 MW have been designed and run as demonstration models in developed countries. Costs of fuel production and power generation are in turn raised by requirements to meet low emission standards.

Even with wastes their use is only economic if marginal costs (labour and machinery) are equal to or less than the value of the energy for which they substitute plus any penalty associated with disposal. The main exception, where current systems are economic, is the in-house use of residues or biogas from effluent treatment within the forest or agro-food industries. With the exception of wood wastes and straw used by direct combustion, almost all other systems will be more expensive than using an oil or coal fired boiler, as far as developed countries are concerned. For developing countries the situation is again made more complex due to questions of self-sufficiency, value of foreign currency and inflation rates as well as the need to service foreign debt. However, in straight cash terms production of liquid fuels such as ethanol, methanol, fatty acid esters and pyrolytic gas may be 1.5 to 3 times as costly as purchasing fossil fuel. The widest range of costs of production is seen with biogas where net costs may range from values as low as US $2 per GJ from industrial effluents, around US $10 from manure, rising to US $30 from sewage sludge or solid waste and as much as US $60 for biogas from energy crops, as compared with natural gas costs of US $4-6 per GJ. These differences reflect those associated with all biomass systems, the marked effect of waste disposal credits, the costs of collection and transport and the costs of purpose grown raw materials. Hence, in-house digestion of effluents for which there would be a disposal charge produces lowest cost gas whilst bought-in energy crops, transported from some distance gives the highest costs.

5.3 Electricity Prices

Electricity generated for own use or for local use in the absence of a national grid system has a completely different set of economic considerations than electricity generated by the small user for sale via the grid. In the first case the main consideration will the cost of purchase of a suitable size generation system, the second consideration will be availability and price of fuel, which has been considered above. In reality the local economics of small power generation from biomass would be compared with opportunities and costs of other renewable systems such as wind, mini-hydro and photovoltaics, with capital cost and ability to construct or service machines with local technicians also important. At present where hydrocarbon fuels are available these may be more economic. In countries such as Brazil with a fuel alcohol programme stationary alcohol fuelled engines can be economic whilst biogas and small gasifiers linked to gas engines are attractive in many developing countries, especially where scrap engines from wrecked vehicles are used.

Small scale generation from biomass for sale via the grid depends on local regulations and tariffs. Provision for such sales exist in many developed countries but tariffs are generally not tailored to encourage small producers. An exception now exists in the UK where legislation coupled to privatisation of the industry is likely to offer the small power producer up to around 6p (US $0.10) per kWh as part of provisions aimed at providing about 15-20% of the electricity from non-fossil sources. In the same way growth of power generation from cane in Hawaii was dependent on legislation. In 1975 the price received from the utilities was around US $0.01 per kWh. The 1978 Public Utilities Regulatory Policies Act (PURPA) required that public utilities purchase electricity at reasonable rates, without discrimination. Section 210 of PURPA (1980) eliminated regulatory impediments and instructed public utilities to purchase power from independent power generators at the avoided cost. This was followed by several other beneficial amendments which resulted in a series of terms of power sales contracts which vary widely depending on prevailing costs of alternative fuels generating capacity and the firmness of the obligation to deliver prescribed amounts of energy for set periods. Electrical energy supplied and generating capacity are treated as two distinct components of power sales. Those with firm contracts obviously receive higher prices, but face severe penalties for non-delivery. The actual contracts vary from payments of over US $1 million for 40 million kWh/y for firm capacity to variable tariffs linked to oil price. Such agreements could be taken as the model for future global expansion of this type of generation. However, in general prices will be lower since those in Hawaii reflect the costs of transporting alternative fuels to a small island in the middle of the Pacific Ocean.

Large biomass systems of 20 to 50 MW are generally run by utility companies with prices linked to the overall business activities of the particular company, reflecting local resources and needs. Hard data is available for one such plant built in the city of Burlington

USA. This 50 MW plant, which cost US $67 million to build, was generating electricity at a cost of 39.5 mills/kWh in 1986 [1].

The cost of electricity generation using a gasifier to produce 500 kWh/h has been estimated by Fonzi [27]. The plant which takes 600 kg/h of wood at 20% moisture, producing 500 kg/h of gas and 240 kg/h steam, generates electricity at a cost of 300 Lit/kWh (US $0.08/kWh). In a wider analysis of electricity production Bridgwater [26] costs gasifier systems of between 1 and 10 MW capacity assuming that one tonne of dry biomass would generate 1 MWh. Prices estimated for straw varied between 4.3 and 6.7 p/kWh and for wood (atr 50% moisture) from 3.58 to 7 p/kWh. These prices were considerably higher than those estimated for similar plant using refuse, which ranged from as low as 1.5 p to 4.0 p/kWh.

6. CONCLUSIONS

It is technically feasible to produce electricity from biomass, grown as an energy crop, or derived by collection of waste, residues or manures as well as through utilization of liquid effluents and solid residues generated in forest product and agro-food industrial complexes. A wide range of conversion technologies have already been demonstrated. Those of greatest use are combustion linked to steam driven turbine, anaerobic digestion linked to gas engine and thermochemical gasifier linked to gas engine. Combustion systems are viable in the MW range, whilst gas engines are suitable for generation in the kW range. Engines may also be run on ethanol, methanol or vegetable oil derived fuels. The possible environmental impacts of large scale removal of residues from the field, large energy plantations and harmful emissions from combustion and engines, as well as conversion techniques such as pyrolysis and biogas production are known and equipment to prevent pollution available. In-house use of wastes and effluents is economic now, as are large wood fuelled dedicated generation systems. Local economics may make the generation of power for export from industrial complexes economic. At present fossil fuel prices production of wood or energy crops is not competitive.

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Fig. 1 Calculated net annual productivities in terms of gram carbon fixed per square meter per year. Approximate dry matter yields can be calculated by multiplying by 2.2

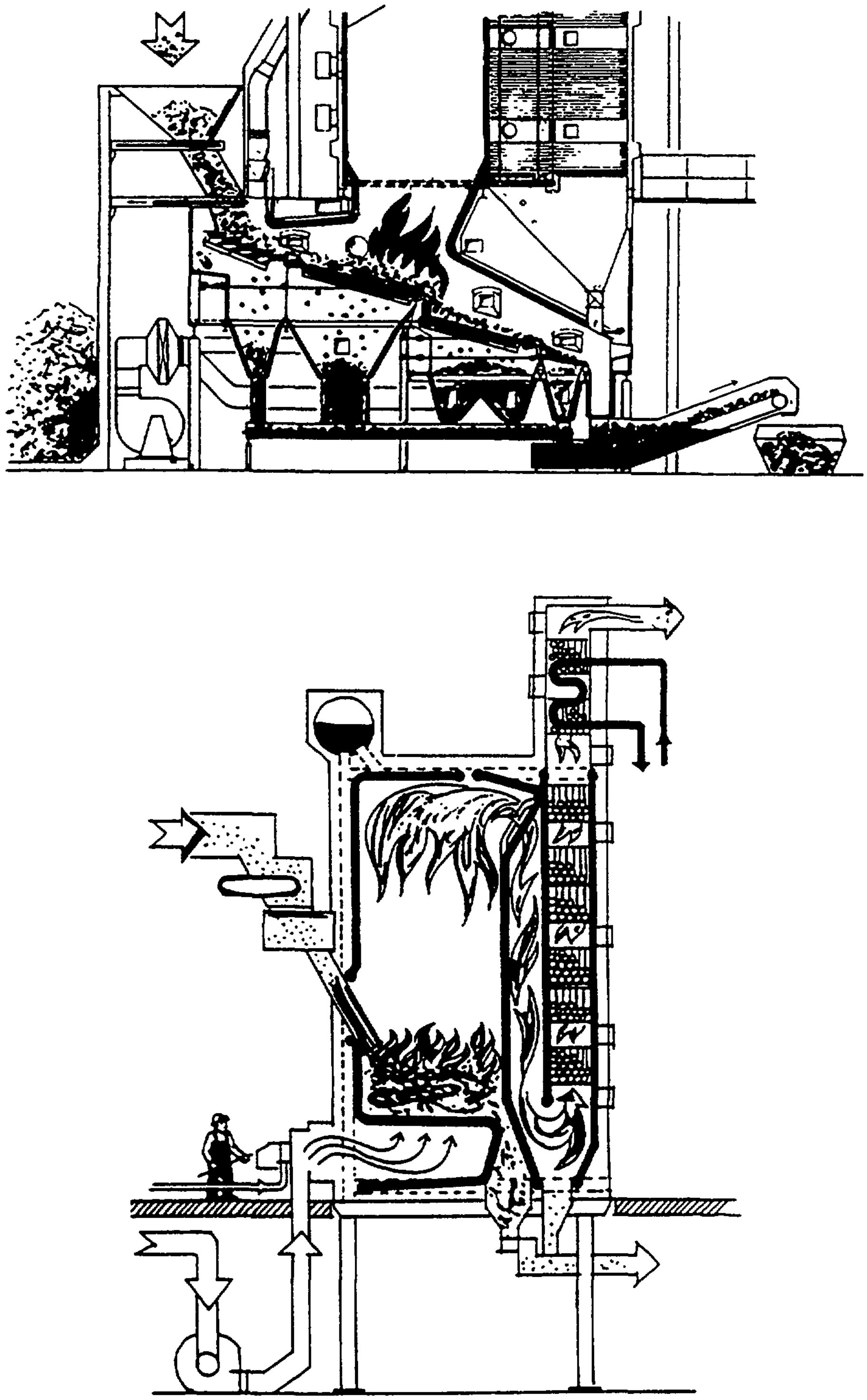

Fig. 2 Typical grates used in large biomass combustion systems. A fixed grate is shown on the top and a fluid bed combustor on the bottom.

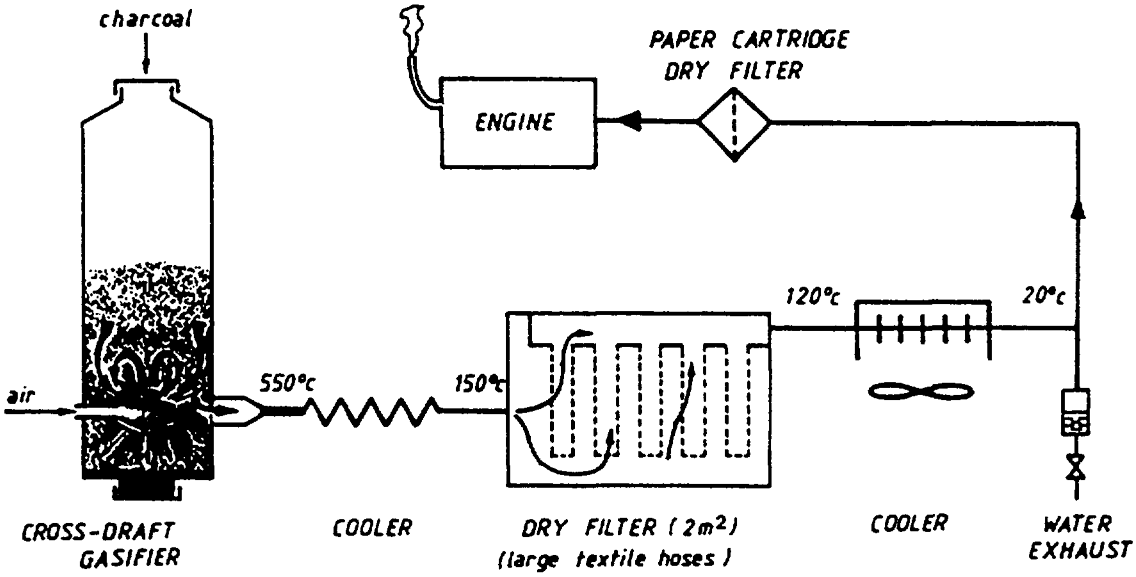

Fig. 3 Flow diagram for a small gasifier producing low HV gas to power an engine driven generator. Note the extent of gas clean up required between gasifier and engine.

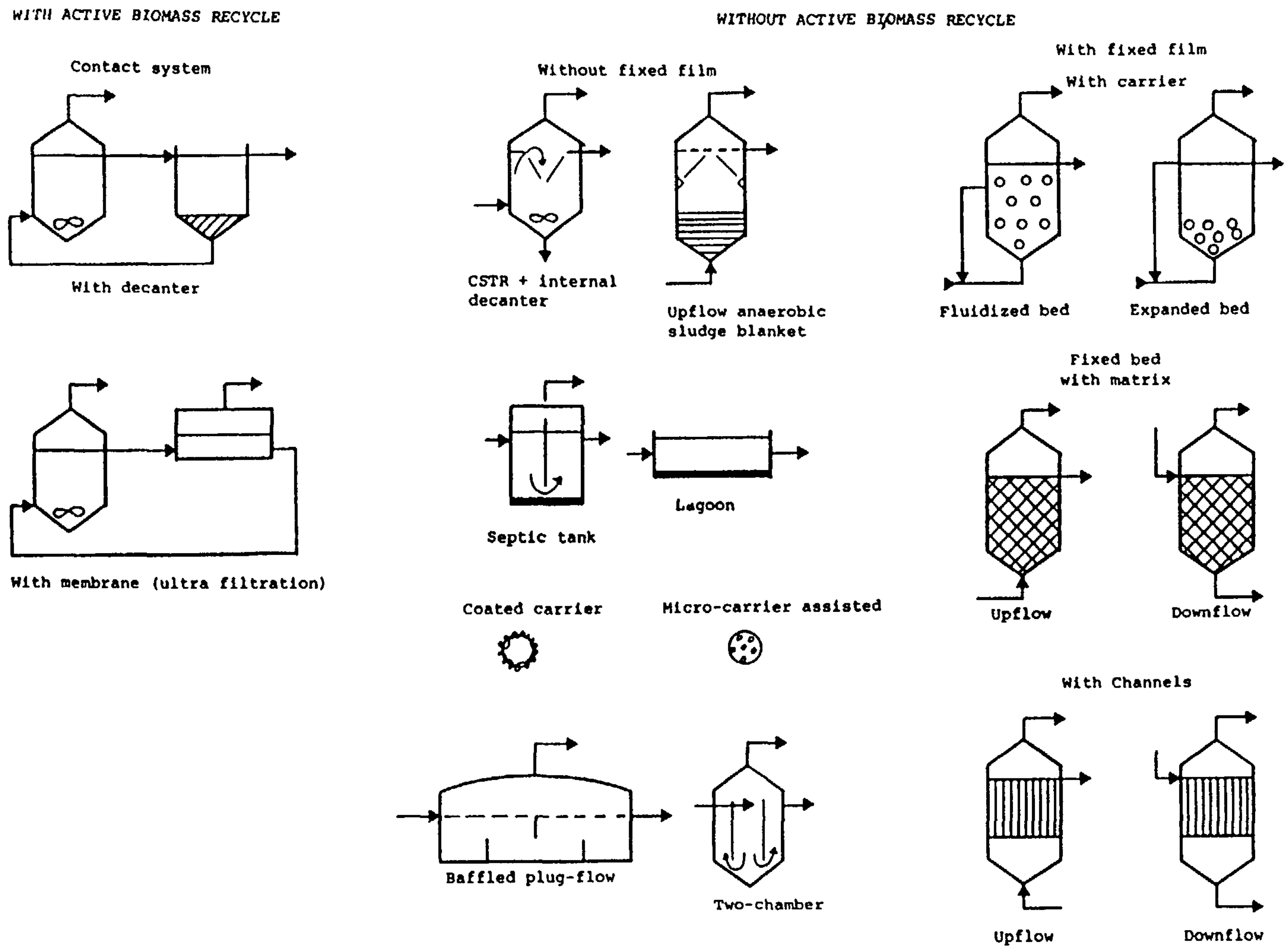

Fig. 4 Schematic representation of the wide range of advanced anaerobic digester designs which have been developed to handle various types of farm wastes and industrial effluents.

OCEAN THERMAL ENERGY CONVERSION

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ABSTRACT: Ocean Thermal Energy Conversion (OTEC) systems utilize the natural temperature difference that exists between the warm waters of the ocean surface and the colder waters of the deep ocean to drive a power plant. This temperature difference, caused by the heating effect of the sun, exists 24 hours a day allowing OTEC plant to operate continuously. It is generally considered that a temperature difference of the order of 20°C would be required for the economic operation of OTEC plant and this may be found in the tropical regions of the world. The principle of OTEC is simple, essentially a lot of plumbing, heat exchangers and a turbo-generator; however the low thermal conversion efficiency when operating with such small temperature differences requires enormous flows of water for a reasonable power output and necessitates enormous components which tend to be expensive. The high capital cost of an OTEC plant suggests that the market will be greatest where its competition, electricity from fossil fuels, is most expensive; for example island communities currently relying on imported oil. Although OTEC has been proven at the small scale and could be expected to operate at a larger one there are few plants to do so and OTEC seems unlikely to play anything more than a minor role as a generator of the world's electricity in the foreseeable future. It is primarily poor economics which militate against its exploitation as a renewable energy technology.

1. INTRODUCTION

In the tropical and sub-tropical oceans of the world a natural temperature difference exists between the surface waters and those at depth. The concept of Ocean Thermal Energy Conversion (OTEC) exploits this temperature difference to drive power plant to produce electricity. The warm surface waters are caused by the heating effect of the sun and OTEC is therefore an indirect solar technology. However, unlike other solar technologies, as the temperature difference remains 24 hours a day, a reliable OTEC plant is able to generate continuously.

The principles of OTEC have been known for over a hundred years. The concept was first proposed by the French scientist D'Arsonval in 1881. In the 1930s, experiments were performed to prove the concept and the first generating station was built at Matanzas Bay, Cuba. This station produced 22 kW_e of power for two weeks before it was partially destroyed in a hurricane, after which the project was closed down. In the late 1950s the French once more became interested in the concept and designed a number of plants one of which was to be built off the Ivory Coast, however, the projects didn't go beyond the design stage due to the lower price of hydro-electric and nuclear power. In the mid 1960s the technology was resurrected by an American team. In the 1970s public concern for the environment and increases in the price of oil led to growing interest in renewable technologies amongst them OTEC. Programmes of research and development commenced in France, India, Japan, Netherlands, Sweden, UK and the USA. At first the emphasis of these research programmes was towards the technological aspects but in more recent years the important economic considerations have been addressed. From a large and varied field of potential schemes in the early 1970s the R&D work on OTEC has settled on a restricted number of schemes. The next few years will see the construction and demonstration of a limited number of small (up to 10 MW_e) schemes and the resolution of some of the questions on the economics and reliability of the technology which have limited its uptake. Given further successful development work and a favourable economic and political climate the technology might be in commercial use by 2010/2020.

2. ENERGY RESOURCES AND RESERVES

The oceans act as an enormous heat sink for solar radiation falling on the earth. About one quarter of the 1.7×10^{17} W of solar energy reaching the earth's atmosphere is absorbed by sea water. In tropical regions the sun's heating effect can lead to surface water temperatures as high as 25°C coexisting with cold water at depths of about 1,000 m with temperatures as low as 5°C. This temperature difference is present 24 hours a day and a reliable OTEC plant can therefore run continuously. Due to the low efficiency, and consequent expense, of power cycles operating with such a small temperature differences OTEC will only be practical for the regions of the world where the greatest temperature difference exists, i.e. 20°C or more. These waters are restricted to the tropical and sub-tropical regions of the world, Fig. 1. The area for possible exploitation is still very large, nearly 60 million km^2, and the potential, unrestricted by economics or technical problems, is orders of magnitude above wind, wave or tidal energy. As an indirect utilizer of solar power OTEC uses a renewable and clean resource.

3. TECHNOLOGIES FOR ELECTRICITY GENERATION

The principle of OTEC is simple and has been described as nothing more than sophisticated plumbing [1]. However, the low thermal conversion efficiency, approximately 2.5%, of an OTEC plant working with such small temperature differences requires enormous flows of warm surface water and cold deep water and necessarily many components are of an enormous size. For example, for an OTEC station of about 100 MW_e, about 450 m^3/s of warm water and the same quantity of cold water must be pumped through the heat exchangers [2]. It is the engineering, cost and reliability of such huge components that limit the prospects for OTEC.

OTEC plants may be based on land or at sea on a floating platform; if afloat they can either be installed on a ship or as a purpose built unit. The essential and distinctive component of an OTEC plant is the large pipe required to bring cold water to the surface. For a 100 MW_e station the pipe could be expected to have a diameter of 20 m and a length of between 600 and 1,000 m depending on location. The power generation components used vary depending on which heat cycle is used for power production. For a floating plant a 100 MW_e station would require an 'island' with a displacement of 200-300,000 tons, Fig. 2. The platform must be stable at sea and allow suitable access for installation and maintenance of equipment. With these considerations in mind large ships are not necessarily the best choice and many designs for purpose built platforms have been made. With a platform positioned in 1,000 m of water mooring is another problem as a fixed position is required to allow electricity to be transmitted to land. To avoid the necessity of a technically difficult mooring it has been proposed that the platform could be self manoeuvering. It would then be possible for the platform to move to areas where the temperature difference is greatest. The drawback to this is that electricity could not be transmitted by cable to the land in which case it would be used in the station itself to produce an easily transportable, energy rich product.

OTEC plants are designed to work with either a closed cycle or an open cycle, Fig. 3. In the closed cycle, warm surface water is pumped through an evaporator in which a working fluid is evaporated. The vapour then flows through a turbine to the condenser where it is cooled and condensed by the cold water pumped up from the ocean depths. The condensate is then collected and pumped back to the evaporator to close the cycle. The working fluid for the closed cycle must be a refrigerant capable of evaporation at the warm water temperature and condensation at the cold. On the basis of cost and safety Ammonia and Freon are the leading candidates.

In the open cycle, sea water is used as both the working fluid and the energy source. The warm sea water is evaporated at very low pressure (0.03 bar) in a flash evaporator. The vapour then passes through a turbine and is condensed either by direct contact with cold sea water or via a surface condenser. If the second method is employed then fresh water is a by-product. For both the open and closed cycles it is the condensation of the vapour which causes a pressure difference across the turbine and the flow of vapour necessary to work it and thereby power a generator to produce electricity. The closed cycle has advantages over the open cycle in that it uses a much smaller turbine and does not require power consuming degassing and vacuum pumps. However, the fresh water produced by the open cycle system could be a valuable by-product for certain locations.

Current research is underway to look at variations on these two basic operating cycles. A variation on the open cycle is the 'mist-lift' cycle. The warm surface water is flash evaporated at the bottom of a tall vertical tube. The warm vapour then rises and at the top of the tube it is trapped and condensed. The condensate is then used to power a water turbine on its way back to sea level. Another alternative cycle which combines aspects of both the open and closed cycles is the 'latent-heat-transfer-closed-cycle-OTEC'. Warm surface water is flash evaporated and the vapour is then condensed against ammonia, the ammonia evaporates and is used to drive a turbine.

3.1 Technical Characteristics of OTEC systems

The technical characteristics of a scheme will necessarily be both design and site specific the following table indicates the range in which some of the key characteristics may be expected to lie.

Unit Size	100 kW_e - 1 MW_e (100 MW_e later?)
Lifetime	30 years
Availability	70 - 90%
Load Factor	70 - 90%
Efficiency	2.5%
Construction Time	3 - 5 years
Planned Maintenance Time	2%

The availability describes the amount of time for which the plant is available to generate power when provided with an exploitable energy resource and is a measure of the reliability of the plant.

The load factor is the ratio of actual electrical units sent out during an average year by the plant to that which could theoretically be sent out if the plant operated at full capacity over a year.

3.2 Activities in OTEC Deployment

There are a number of projects currently underway and planned in the eight countries active in OTEC research and development.

Within the United Kingdom designs for a 10 MW_e closed cycle plant to be installed in the Caribbean or Pacific have been completed. A 500 kW_e closed cycle onshore plant combining freshwater production and mariculture to be installed in Hawaii is being designed.

The Dutch have completed feasibility studies for a 10 MW_e floating plant in the Dutch Antilles and a 100 kW_e onshore plant for Bali but funding has now ceased.

Interested parties in Jamaica, Sweden and Norway have agreed to develop a 1 MW_e unit in Jamaica.

The French have decided to build a 5 MW_e onshore plant in Tahiti; however, problems were encountered which have postponed the commissioning date.

In Japan the government is designing a 10 MW_e floating plant and is considering a land based scheme. The government is also sponsoring research into a combined OTEC and mariculture scheme using a 5 kW_e plant.

In Taiwan there are plans for a 9 MW_e unit to utilize discharged cooling water from a nuclear plant at Hon-Tsai. This scheme has the advantage that it would provide a high temperature difference for the OTEC cycle and would reduce the environmental impacts of the cooling water discharge.

The United States is proceeding with a conceptual design of a 100 MW_e closed cycle plant for Puerto Rico.

4. ENVIRONMENTAL ASPECTS OF ELECTRICITY GENERATION

The operation of an OTEC plant may have a number of environmental impacts, most of these are difficult to assess. The large flows of hot and cold water required by an OTEC plant lead to the possibility of local or even global weather modification.

There is also the possibility of carbon dioxide being released from deep ocean water into the atmosphere. This is because the deep ocean waters contain a greater concentration of carbon dioxide than the surface waters and as they are heated in the condenser some carbon dioxide may be released. This is a more serious problem for an open-cycle plant as the warm water must be de-aerated before it is flash evaporated. It has been estimated that an open cycle OTEC may release as much as 30% of the carbon dioxide produced by an equivalent capacity fossil fired plant.

OTEC may also have serious impacts on marine life. It is thought that fish, eggs and larvae taken up by the plant may be harmed and that changes in temperature and salinity may affect the local ecosystem. There are concerns that certain biocides, such as chlorine, required to control marine fouling may also be harmful although the concentrations required are low.

Freon has been proposed as a working fluid for some closed cycle schemes, as it is a CFC, i.e. a highly damaging 'Greenhouse Gas', this would not be advisable from an environmental point of view. There are, however, effective alternatives to Freon available.

5. ECONOMICS OF ELECTRICITY GENERATION

The economics of OTEC will be paramount in determining its future and will decide whether it will eventually become an energy technology in wide use within the tropics; a technology only suitable for certain specific locations where the cost of alternative energy sources are high, or an unfortunate commercial failure. With only a few small scale plants built for feasibility studies it is difficult to accurately assess what the costs of a much larger commercial plant would be, especially as the prospect of such a scheme is some years away. Present designs for an OTEC plant give capital costs of the order of US$ 10,000/kW installed (in constant prices of 1989). An OTEC plant could conceivably be designed for unattended operation with consequently low operating costs of the order of US cent 0.8/kWh. Considering these costs together, the cost of electricity generation could be expected to be somewhere in the range US cent 12-25/kWh. However, the cost of electricity could be lowered if there were a market for the fresh water byproduct or if the scheme were to be linked with a mariculture product.

6. CONCLUSIONS

The thermal resource required by OTEC plants - i.e. a temperature difference of approximately 20°C - lies predominantly between the tropics of Cancer and Capricorn. The countries which lie within this geographical band and could therefore exploit OTEC are for the most part developing nations and many of them are islands. This suggests that if commercial

OTEC schemes are developed they are likely to be on a small scale, probably less than 1 MW_e. The market for OTEC will be greatest where its competition, electricity from fossil fuels, is most expensive. Island communities which have to rely upon imported oil, and pay a premium price for it, are an obvious target. However, because of the vagaries of international oil prices this market is difficult to assess. Large grid connected plants intended to act as base load on the electricity system of developed countries are less likely to be seen and are not anticipated for at least a decade.

OTEC seems unlikely to play anything more than a very minor role as a generator of the world's electricity in the foreseeable future. Although OTEC has been technically proven at a small scale and could be expected to operate at a larger one there are few plans to do so. It is primarily poor economics which militate against its exploitation as a renewable energy technology for electricity generation. The high costs associated with OTEC can be seen to lie with the inescapable low efficiency of the heat-power cycle which leads to the large size of certain components required to handle the enormous water flows which are necessary when operating at such small temperature differences. There are possible cost reductions to be made by improvements in heat exchanger and cold water pipe design.

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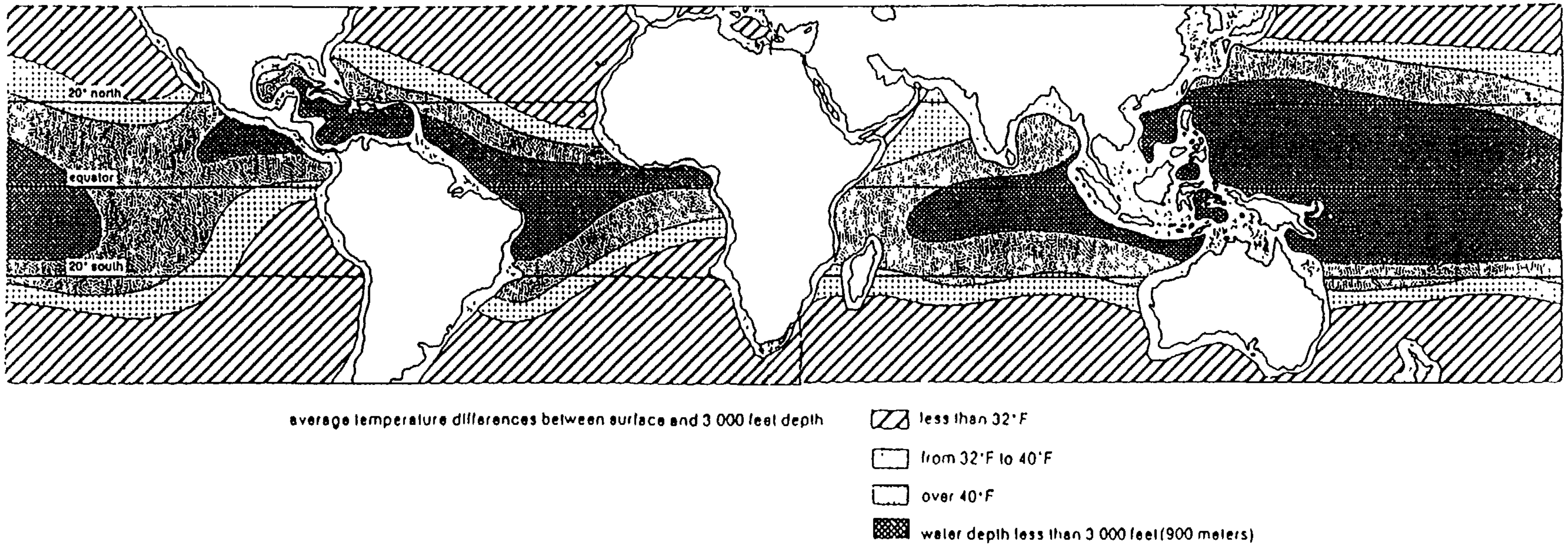

Fig. 1 Thermal Resource Map of the World's Oceans.

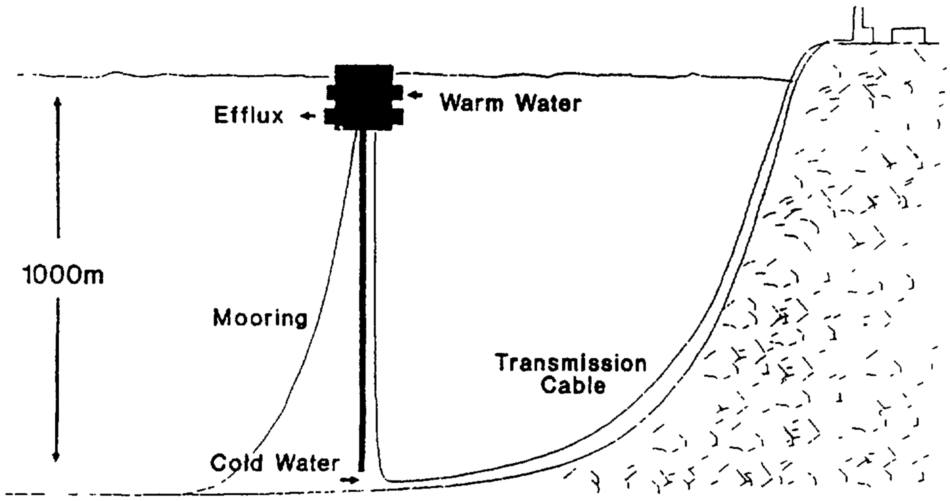

Fig. 2 OTEC Floating Platform Schematic.

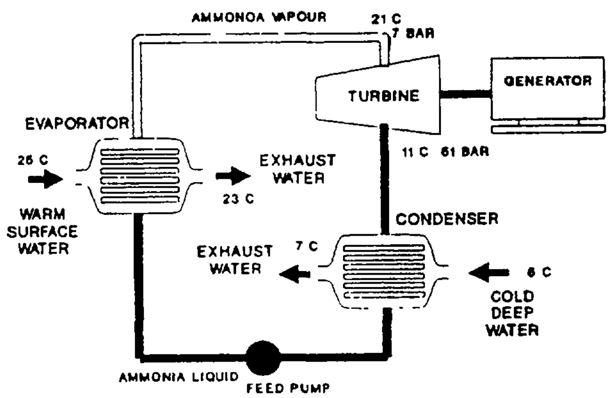

Fig. 3a Closed Cycle.

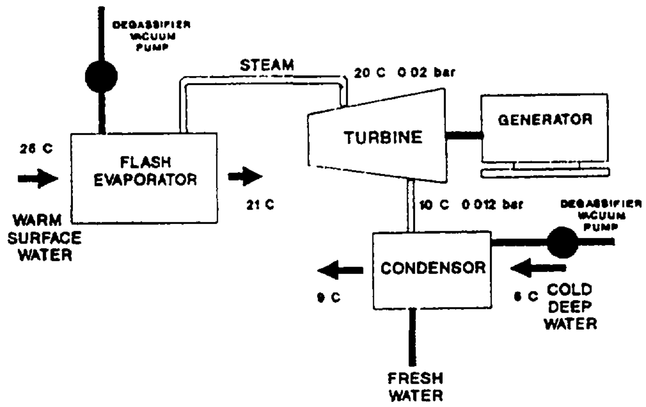

Fig. 3b Open Cycle.

TIDAL ENERGY

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ABSTRACT: This paper describes tidal energy systems as a technology for electricity generation. After a consideration of the nature of tides and the potential world tidal energy resource the paper describes the present status of the technology, the elements which make-up a tidal scheme and the proposed methods of operation and construction. The environmental implications of tidal schemes are dealt with. The final section considers the economics of tidal power with particular reference to the proposed Severn tidal barrage in the UK.

1. INTRODUCTION

Man's use of tidal energy is not new. Tidal mills were first in use in the eleventh century along the coasts of England, France and Spain and some of these were in operation up to 40 years ago. The prospects for electricity generation from tidal energy were first considered early this century, and the first full scale tidal energy generation scheme was built at La Rance, France in 1966.

Tides are caused by the gravitational attraction of both the sun and the moon acting upon the rotating earth. The energy in the tides is obtained from the slowing of the earth's rotation. The slowing effect is almost imperceptible on a human timescale and tidal energy can sensibly be considered a renewable energy. Tidal power is not supplied continuously being dependent on the two daily tides and a number of other cycles including half monthly, monthly and longer (20 year). However, although power production from a single basin scheme is necessarily intermittent it is entirely predictable and its anticipated production can be determined for any future date.

A considerable number of devices have been proposed to harness potential or kinetic tidal energy none of which appears to have any advantage over the traditional approach of filling a basin at high tide and later allowing the water to return to sea level through a hydro-turbine; generating power while doing so.

2. ENERGY RESOURCES AND RESERVES

The surface of the waters of the earth, rise and fall approximately twice each day in response to gravitational forces exerted by the sun and the moon. Although the sun is 27×10^6 times as massive as the moon, it is 289 times further away. Consequently, the main tidal force is that of the moon, being about 2.2 times that of the sun.

During the earth's daily rotation upon its axis a point on its surface will encounter two raised and two depressed bodies of water - a so called semi- diurnal regime. The relative motion of the earth, moon and sun causes an average of 1.94 tidal cycles or 3.87 tidal oscillations every 24 hours, equivalent to a high water to high water period of about 12 hours 25 minutes. The semi-diurnal cycle is accompanied by a Spring-Neap Cycle, due to the occurrence of maxima and minima in the combined effect of the gravitational fields of the moon and the sun. This gives rise to a period of about 28 days (actually 57 tides) between successive spring (or successive neap) tides. This is modified on a monthly basis because the Moon's orbit is an ellipse. The successive spring-neap cycles can vary in amplitude by around +15%. Furthermore, a Semi-Annual cycle, due to the inclination of the Moon's orbit to that of the Earth, gives rise to a period of about 178 days between the highest spring tides, which occur in March and September, and may introduce a perturbation of +11% the normal tidal range.

Tides do not occur everywhere. Indeed, there are several points in European waters, which experience almost no tides at all, for example in the Baltic and Mediterranean seas. In the UK the amplitudes of these cycles are at their maximum around the western coast, reducing with longitude around the Scottish coast and with latitude along the south coast. The amplitudes are increased substantially in estuaries, by local effects such as shelving, funnelling, reflection and resonance (Fig. 1).

The amount of energy available from the tides is approximately proportional to the square of the tidal range. The energy available for extraction by a tidal power plant would therefore vary by a factor of around four over the 14 day Spring-Neap Cycle. Although the time of high water advances about an hour each day, preventing the tailoring of energy output to load demand, the tides are nevertheless completely predictable, and therefore, the total electricity generating system (or a part of it) could be pre-scheduled to make optimum use of the tidal energy resource.

Tidal schemes will be practical only where there is the conjunction of a high tidal range and suitable coastal geography to provide a site. This limits considerably the number of possible sites, however many have been identified and it has been estimated that world-wide there is a potential economic resource of about 200 TWh per year or about 1% of the total theoretic potential (Table I).

Table I. Tidal Power World Potential - Leading Sites.

		Installed Capacity (MWe)	Approximate Annual Output (TWh)
Argentina	San Jose	6,800	20.0
Australia	Secure Bay 1 & 2	ca. 3,000	7.8
Canada	Cobequid	5,338	14.0
	Cumberland	1,400	3.4
	Shepody	1,800	4.8
India	Gulf of Kutch	900	1.6
	Gulf of Cambay	7,000	15.0
Korea	Garolim	480	0.53
	Cheonsu	ca. 400	1.2
Mexico	Rio Colorado	ca. 2,000	5.4
UK	Severn	8,640	17.0
	Mersey	700	1.5
	Morecambe	3,040	5.4
	Other small schemes	1,000	2.0
USA	Knik Arm	2,900	7.4
	Turnagain Arm	6,500	16.6
USSR	Mezenskaya	15,000	50.0
	Turgursk	7,000	27.0
	Penzhinsk	20,000	79.0
TOTAL		74,698	279.6

3. TECHNOLOGIES FOR ELECTRICITY GENERATION

3.1 Present Status of the Technology

Pilot scale tidal power schemes overseas have been generating electricity at in France, Canada, the USSR and several small schemes on the south east coast of China. On the basis of these schemes Tidal power can be regarded as proven at the small (100 MW_e) scale, successful larger developments have yet to be seen.

Prospective tidal energy development is confined to regions with large tidal ranges - greater than 5m - and coastlines with suitable sites for barrage construction. These criteria limit potential development to a few areas of the world, however, there is growing interest, particularly in the UK. The largest operational power station, built at La Rance in France, with an installed capacity of 240 MW_e, has been generating reliably and economically since 1966. Since then a 20 MW_e plant has been built at Annapolis in Canada. A smaller 400 kW_e experimental station at Kislaya Guba in the USSR and a 3.2 MW_e plant at Jiangxia in China have also been constructed. Operational experience from these stations has demonstrated that only minor modification is required to overcome design weaknesses.

Technology specifically for tidal energy applications has been developed over the last thirty years since La Rance was opened. Feasibility studies in both Canada and the UK have greatly expanded technological expertise. Axial flow turbines have been designed for variable low-head application and at La Rance bulb turbines were adapted for this operational mode. At Annapolis a rim-generator (Straflo) turbine has been tested. Compressed air turbines have also been contemplated for future projects, although their use remains at a conceptual stage. Construction techniques have also been reviewed.

Cofferdams, which were used to construct La Rance, are now considered inappropriate for large schemes in deep water and also where the barrage construction method must allow maximum permeability and access upstream of any structure. Prefabricated caissons would most likely be used in future projects. This allows early closure, minimal embankment and fabrication at different localities with obvious advantages for competitive construction. These could be made of either concrete or steel.

Advances continue to be made in other areas of research and development aimed at optimizing installed capacity, maximizing plant output and integrating output into utility systems. Results from these studies now favour the ebb generation mode, to gain maximum energy output. Limited flood pumping can often enhance energy output by a few percent. Hydrodynamic models have also been improved and allow prediction of energy output from potential sites.

3.2 Basic Components of an Energy Barrage

Tidal power involves impounding a large body of sea water with a sufficiently high tidal range and generating hydroelectric power as the water passes through turbines.
The necessary major components of any tidal energy barrage, therefore include:

- sluices, which allow water into (or out of) the enclosed basin;
- turbine-generators, which convert the flow of water into shaft rotation and thereby into electricity;

- ship locks, where necessary, to permit continued navigation;
- embankments, to complete the barrage across the estuary.

3.3 Principles of Energy Extraction

For any tidal power barrage, the quantity of electricity produced is constrained by a number of practical considerations but would largely depend on the number and size of turbines. This in turn is dependent upon the water depth and tidal range available and, of course, the length of barrage and the volume of water it is able to capture.

There are several possible modes of operation of a tidal power plant, namely (Fig. 1):

- ebb generation, with or without pumping;
- flood generation;
- two-way generation.

Ebb generation allows the rising tide to flow in through the sluices and turbines (which idle in reverse). Both sluices and turbine water passages are then closed soon after high tide. These are kept closed until the tide has ebbed and the difference in water level between the barrage and the sea (the available hydraulic head) is sufficient to drive the turbines and their generators. The water is then allowed to flow through the turbines until the difference in water level is inadequate to turn them efficiently.

Pumping (from sea to basin) may be associated with any of the above modes but is usually referred to in connection with ebb-generation. The net head against which the work of pumping has to be done is significantly less than the net head that becomes available for generation later in the cycle from the same volume of water. This results in a small net increase in energy output, typically of the order of 5-10%, but may be as much as 15% in certain circumstances. Pumping can also increase the value of the electricity generated by allowing limited rescheduling of output to meet demand. The increase in value of energy can therefore be greater than the increase in energy produced.

Flood generation has never been considered seriously since, for a given location, it cannot generate any more energy than an ebb generation scheme and in addition, it has adverse implications for both shipping and recreation and can have severe environmental impacts.

The principal alternative mode of generation is that of Two-Way Generation, generating on both the flood and the ebb. The main attraction of this operating regime is that it enables electricity to be produced during a greater proportion of the day. It might also result in greater operational flexibility. However, there are a number of drawbacks. Firstly, studies have shown that for a barrage containing any given number of turbines, slightly less energy would be produced by two-way generation than by simple ebb generation. This is because the head of water at the start of generation in either direction is much less with two-way generation than with one-way generation. Also, with two way generation the turbine would operate less efficiently at any given head, since turbine blades and water passageways can only be fully optimized for a single direction of flow. To attempt to optimize in both directions would result in both more expensive rotating plant and much wider turbine caissons leading again, to an increase in capital cost. Secondly, Two-Way Generation has been shown to be typically 15-20% more expensive for a barrage of a given energy output, mostly as a result of the larger number of turbines and turbine caissons which would be required. These increases would not be fully offset by savings in the cost of sluices, generators and electrical transmission (peak supply being reduced). A further factor is the effects on shipping resulting from the new upstream water levels with two way generation. These would be limited to about mid-way between the present mid and high tides and this would have a severe effect on any river traffic particularly commercial shipping. The reduction in water levels from those pertaining to ebb generation would also, of course, significantly reduce the regional development opportunities which are expected to accrue by having a 'marine lake' upstream of the barrage.

It is clear from the above, therefore, that the most promising mode of generation of a tidal barrage appears to be ebb-generation, with limited pumping at the end of the flood tide. This is the preferred mode of operation for all the tidal power schemes presently under consideration in the UK, including both the Severn and Mersey projects.

3.4 Tidal Power Engineering - Civil Engineering Design

There are a number of construction methods available to civil engineers designing a tidal power barrage. The original method for constructing the French La Rance scheme involved the use of a temporary coffer-dam behind which the barrage was constructed in-situ, in the dry; the coffer dam was then removed. This method is expensive and environmentally damaging. It is also unsuitable for large schemes in deep water.

The method now generally preferred employs caissons. These are large preformed structures usually of concrete but possibly of steel or 'composite' construction. The caissons would house either the turbine-generators and associated electrical equipment (transformers, switchgear) or the sluice gates, plain caissons and embankment would be used to complete the structure.

Caisson technology is well tried and tested, and could be used for all but the very smallest of schemes where water depth or other problems of access might prevent the floating-in of caissons from seaward approaches. Caissons could be designed to hold any number of turbines (typically between 1 and 4) or any number of sluice gates (probably between 1 and 3). The final design is determined from a complex myriad of considerations, but floating draft, floating stability, in-situ stability, operating philosophy and maintenance requirements are of paramount importance (Fig. 3).

A possible alternative to the caisson method is that of in-situ diaphragm walling. This involves the construction and protection of an artificial sand island across the estuary, which is then used as a base for the excavation of conventional diaphragm walling. With the diaphragm walls in place and complete, the sand is removed and permeability achieved by breaking through sections where necessary. Various methods of protecting the temporary sand island have been considered, including the sinking of redundant large oil tankers.

Once an approximate barrage line has been selected on the basis of considerations of energy output, costs and environmental impacts, the precise line then needs to be fixed to take into account local geology, exact scheme details (e.g. position of shiplocks) and local environmental factors (eg. avoiding sensitive landfalls).

3.5 Mechanical and Electrical Design

Low head hydraulic power is characterized by high volume flow turbines, with horizontal axis and carefully designed passages aimed at minimizing losses from directional changes of water flow. Low head applications demand units with high specific speed with either variable blades or variable distributor (or both) for regulation. Since the 1930s, two arrangements of turbine generator have been dominant - the bulb and the rim generator.

3.6 The Bulb Turbine Generator

The generator is placed in line and coaxially with the turbine, upstream of it, and within a water tight casing that forms the inner boundary of the annular water passage. The 'bulb' is placed up-stream so as not to be a factor in head recovery by the draft tube. Air cooling of the generator is preferable and has the added advantage that the increased inertia of a slightly higher diameter improves stability and eases synchronizing. As the head of water across the turbine varies, the operation of the turbine is optimized by varying the angle of the runner blades or the angle of the guide vanes in the distributor. Double regulated machines, Kaplans, are needed if pumping is required. Large numbers of bulb turbines of diameters up to 10m are in operation in run of river schemes around the world. The La Rance tidal scheme uses 24 five meter Kaplans.

3.7 Rim Generator Sets

The rim generator machine (or Straflo) is an alternative configuration. Here the generator is in the same axial plane as the turbine and its poles are mounted on a ring fixed to the rim of the blades and rotating with it. The rim generator is simpler, has a shorter axial length (which can reduce civil engineering costs) and a higher inertial constant which improves the stability of the system. The crucial design feature of the Straflo is that the water seal (between the generator and the turbine) is shifted from the shaft to the outer rim, where the diameter and surface to be sealed are far greater. This matter has attracted a great deal of development work over the last 20 years and a seal configuration has been achieved which has been proved in service. However, it means that a Straflo machine should not be specified in waters containing excessive amounts of solids which could interfere with the behaviour of the seal. The main disadvantage of the Straflo is limited operational experience. Also large double regulated Straflo machines are not operationally proven in applications where they must alternately generate and then pump.

3.8 Unit Control

To ensure that the machines are brought on stream at exactly the correct time with the minimum of lost energy, a pre-programmed starting and stopping schedule is envisaged. This will be derived from considerations of tide, load, other generating plant and transmission system losses within the area (or nationally). However, the main objective will be to maximize the value of the energy provided.

3.9 Technical Characteristics of Tidal Barrages

The technical characteristics of a scheme will necessarily be both design and site specific the following Table II indicates the range in which some of the key characteristics may be expected to lie.

Table II. Key characteristics of Tidal Barrages.

Unit Size	10 MWe - 20 GWe
Lifetime	120 Years civil engineering structure 40 years mechanical and electrical components
Availability	98%
Load Factor	20 - 40%
Efficiency	93%
Construction Time	3 - 10 years
Planned Maintenance Time	2%

The availability describes the amount of time for which the plant is available to generate power when provided with an exploitable energy resource and is a measure of the reliability of the plant. The load factor is the ratio of actual electrical units sent out during an average year by the plant to that which could theoretically be sent out if the plant operated at full capacity over a year.

4. ENVIRONMENTAL ASPECTS OF ELECTRICITY GENERATION

The most marked effects of an operational tidal barrage relate to water movements. The precise nature of this effect depends, amongst other things, upon the mode of operation (this is very evident from Fig. 2). With ebb generation, the post-barrage upstream water levels vary between the approximate mid-tide and high tide levels of the pre-barrage situation. Whilst there is some reduction in the high tide levels (which may affect river traffic for deep drafted vessels), the main environmental effect is that of raised water levels upstream of the barrage and the submergence of what may have been inter-tidal mud flats and the subsequent loss of (possibly important) bird feeding areas. Where an estuary has significant numbers of wading birds that use the inter-tidal areas for winter feeding, there are likely to be strong objections to any barrage development. This situation is further aggravated by the (slightly) reduced high water levels and the subsequent reduction in saltmarsh inundation which is believed to effect wild fowl.

One further effect of a barrage is the general reduction of water current strength, both upstream and downstream. Post barrage current strengths are typically one half to one third their original values. This result is predictable and arises because water flows are little affected, while water depths are generally greater at times of maximum flow. Currents are most affected on spring tides, with values on neap tides being generally comparable with their original values.

These two principal hydrodynamic effects, water levels and current velocities give rise to a number of changes in the fundamental properties of the estuary: sediments, salinity and water quality. In general, the most significant and controversial of these is sediments. The general reduction in water currents could in some cases give rise to increased deposition of sediments in the basin and this may be a problem if there is a large source of such sediments outside the barrage. Furthermore, whilst the general trend is for reduced currents, there are likely to be areas where local currents greatly exceed the natural mean, for example, in the vicinity of sluices and turbines. The positioning of these barrage elements is therefore very important if their functioning is not to give rise to problems of sediment erosion and re-deposition. Deposition of sediments within the basin area may, or may not, constitute a serious problem. In estuaries where large amounts of fine sediment exist downstream of the barrage line, construction of a tidal scheme might cause movement of sediment into the basin, which would then silt up. However, minor amounts in low water channels could easily be dealt with by increasing dredging accordingly. Furthermore, deposition of fine sediments on sand banks could, theoretically, improve ecological productivity and transform once barren areas into feeding places for birds. This is a factor which has yet to be fully assessed.

Construction of a tidal power barrage also results in an increased 'flushing time' for an estuary. If an estuary is a sink for sewage and detritus, a possible consequence of this may be a further reduction in water quality. In general, this is not believed to be a major cause for concern. Some argue that the reduced turbidity and improved oxygen levels in the water column may benefit aquatic ecosystems and accelerate destruction of sewage borne bacteria.

For estuaries with important fish populations, it is necessary to ensure their safe passage through the barrier, especially for migratory species such as salmon. From experience of run of river schemes using similar machines, the mortality rate for young fish descending through the turbines can be acceptably low. Also fish passes or surface spillways can enable many fish to avoid the turbines. However, there is some uncertainty about the effect of pumping on large adult fish moving upstream through the turbines. This requires further investigation.

In conclusion, it must be said that there remain several significant uncertainties with respect to the general environmental effects of tidal energy. Clearly the larger a particular scheme, the greater the potential for change, although not all these changes are detrimental. However, even for the smallest of tidal energy barrage projects, the nature of potential impacts must be identified and studies undertaken to demonstrate that the general effects of these are acceptable.

4.1 Regional Development Opportunities

In addition to the considerable environmental issues discussed above there are significant regional development opportunities which undoubtedly favour tidal schemes. These regional benefits arise, not only from the construction and operation of what may be a substantial power station development, but also from the changed water levels and reduced current velocities in the post-barrage situation. The barrage could be designed to carry a public road and so improve communications in what may be remote and isolated districts. The marine lake formed upstream of the barrage might provide the necessary incentive for riverside residential and commercial developments. Increased water levels and changed currents are also likely to encourage water sports and recreation which together with the barrage as a major attraction will lead to a significant tourist trade. This has certainly been the net effect at La Rance, which enjoys 250,000 tourists each year.

5. ECONOMICS OF ELECTRICITY GENERATION

Tidal barrages are capital intensive with investment costs of the best schemes around US$ 1,500-2,000/kW (in prices of 1989); these costs being very much site dependent. However, once built the costs are essentially fixed. This is not the case for conventional fossil plant where the cost of energy is dependent on the price of fuel as it is to some extent for nuclear power. If there were to be significant rises in fuel prices, the relative economics of tidal energy would improve. The lifetime of tidal energy schemes is very long (100 years or more) compared with the period over which the capital costs may be paid off. Once this has been done electricity may be produced for many decades at very low cost.

As an example of the technical and economic characteristics of a tidal barrage, the following results from the recent, Severn Barrage Report [1] are presented (Table III). The

Table III. Technical and Economic Characteristics of the Severn Barrage, United Kingdom

Technical Data	Number of turbine generators	216	
	Diameter of turbines	9 0 m	
	Operating speed of turbines	50 rpm	
	Turbine generator rating	40 MWe	
	Installed Capacity	8,640 MWe	
	Number of sluices, various sizes	166	
	Total clear area of sluices	35,000 m^2	
	Average annual electricity output	17 TWh	
	Operating mode	Ebb generation with flood pumping	
	Barrage length	15 9 km	
	powerhouse cais	4 3 km	
	sluice caissons	4 1 km	
	other caissons	3 9 km	
	embankments	3 6 km	
	Area of closed basin at mean sea level	480 km^2	
Cost Estimate (on basis US$ April 1988)		US Dollar millions	% of Total
Pre Construction Phase	Feasib & environm studies planning and parliamentary costs	110	0 7
	Design & engineer	245	1 6
Barrage Construction	Civil engineering works	9 200	59 1
	Power generation works	4 500	28 9
	On-barrage transm & control	710	4 6
	Management engineering and supervision	560	3 6
	Land and urban drainage sea defences	55	0 4
	Effluent discharge, port works	150	1 0
TOTAL BARRAGE COST		15 550	100 0
	Off-barrage transmission & grid reinforcement with all transmission lines overhead	1 600	
	Extra cost for 10% of transmission lines underground	710	
Annual Costs	Barrage operation and maintenance	75	
	Off-barrage costs	55	
TOTAL ANNUAL COSTS		130	

Severn Barrage is a proposed tidal energy scheme to be situated in the Severn Estuary which feeds into the Bristol Channel on the south-west coast of the United Kingdom (Fig. 4).

With considerable capital investment some years prior to first generation the economics of tidal barrages are highly sensitive to the discount rate. For example, the following Table IV shows the variation in cost of generation with discount rate for the Severn Barrage.

Table IV. Variation of Generation Costs with Discount Rate (based on 1989 cost values)

Discount Rate	2%	5%	8%	10%	12%
Cost of electricity (USc/kWh)	2.9	5.8	9.5	12.5	15.6

The following Table V presents cost estimates for a number of tidal schemes [2].

Table V. Cost Estimate for selected Tidal Schemes (Costs at US$ 1989)

Scheme	Installed Capacity (MWe)	Annual Output (GWh)	Capital Cost (million US$)	Generation Cost (US cent/kWh)
Severn Barrage, UK	8,640	17,000	13,850	5.8
Morecambe, UK	3,040	5,400	7,230	9.3
Solway, UK	5,580	10,050	15,000	9.8
Mersey, UK	620	1,320	1,360	7.2
La Rance, France	240	544	-	6.9
Fundy B9, Nova Scotia	4,964	14,004	9,088	4.5
Garolim Bay, South Korea	480	893	550	4.2

The costs were estimated in sterling (1989) using a 5% discount rate and have been converted using the 1989 dollar:sterling exchange rate (1.6 US Dollar = 1 Pound Sterling)

A parametric method of estimating the costs of energy from tidal barrages has been developed by Binnie and Partners [2] in the UK to enable approximate cost of electricity from potential schemes to be evaluated simply and quickly (Fig. 5).

$$U = [L^{0.8}(H+2)^2/(A(R-1)^2)]^k$$

where U is the cost of electricity generation in p/kWh
k is a constant
R is the mean tidal range in meters at the barrage site
A is the area of the enclosed basin in km^2
L is the length of the barrage in meters
H is the maximum depth of water along the line of the barrage.

This method has been employed to evaluate potential sites on the west coast of England and Wales. The parametric model is based upon a theoretical model of the costs of tidal energy and calibrated using data from schemes, actual and potential, some of which are shown in the above table.

6. CONCLUSIONS

Harnessing the power of the tides by way of a barrage is a proven technology; a number of small schemes are currently in successful operation and there are commercially available methods for the construction of large schemes in deep water.

Tidal barrages are unlikely to present any major environmental problems provided there is sensitivity towards local environmental issues when siting. Barrages may afford environmental benefits, for example, protection against storm surge tides. There are no global environmental impacts, such as emissions, from the operation of a tidal barrage.

The economics of tidal power are necessarily strongly dependent on the choice of site and especially sensitive to the tidal range. Sites with a mean spring tidal range of less than 5 m are unlikely to be cost effective; the energy flow through a barrage being proportional to the square of the tidal range.

They are also dependent on the method of financing. With considerable capital investment required some years before first generation, the choice of discount rate may well determine the viability of a project. For example; for the proposed Severn barrage in the UK, an increase in the discount rate from 5% to 10% will more than double the cost of energy.

Tidal barrages have a high capital cost but very low running costs and have unusually long plant lifetime. With reasonable maintenance this may be greater than a 100 years. The lifetime is therefore very long compared with the period over which the capital costs would be paid off.

No clear economy of scale exists for tidal barrages. Good schemes can be identified with scales that range over two orders of magnitude, (30 MW_e - 8,000 MW_e) with comparable costs of electricity.

In addition to the value of the electricity produced, non-energy benefits can be important locally; for example, road crossings, water based recreation and amenity, increased land values.

The prospects for tidal energy are favourable where there is the conjunction of an economically attractive site, supporting non-energy benefits and investors prepared to value the long term benefits of a capital intensive project. Where this combination of circumstances occurs a limited uptake of tidal energy may be anticipated.

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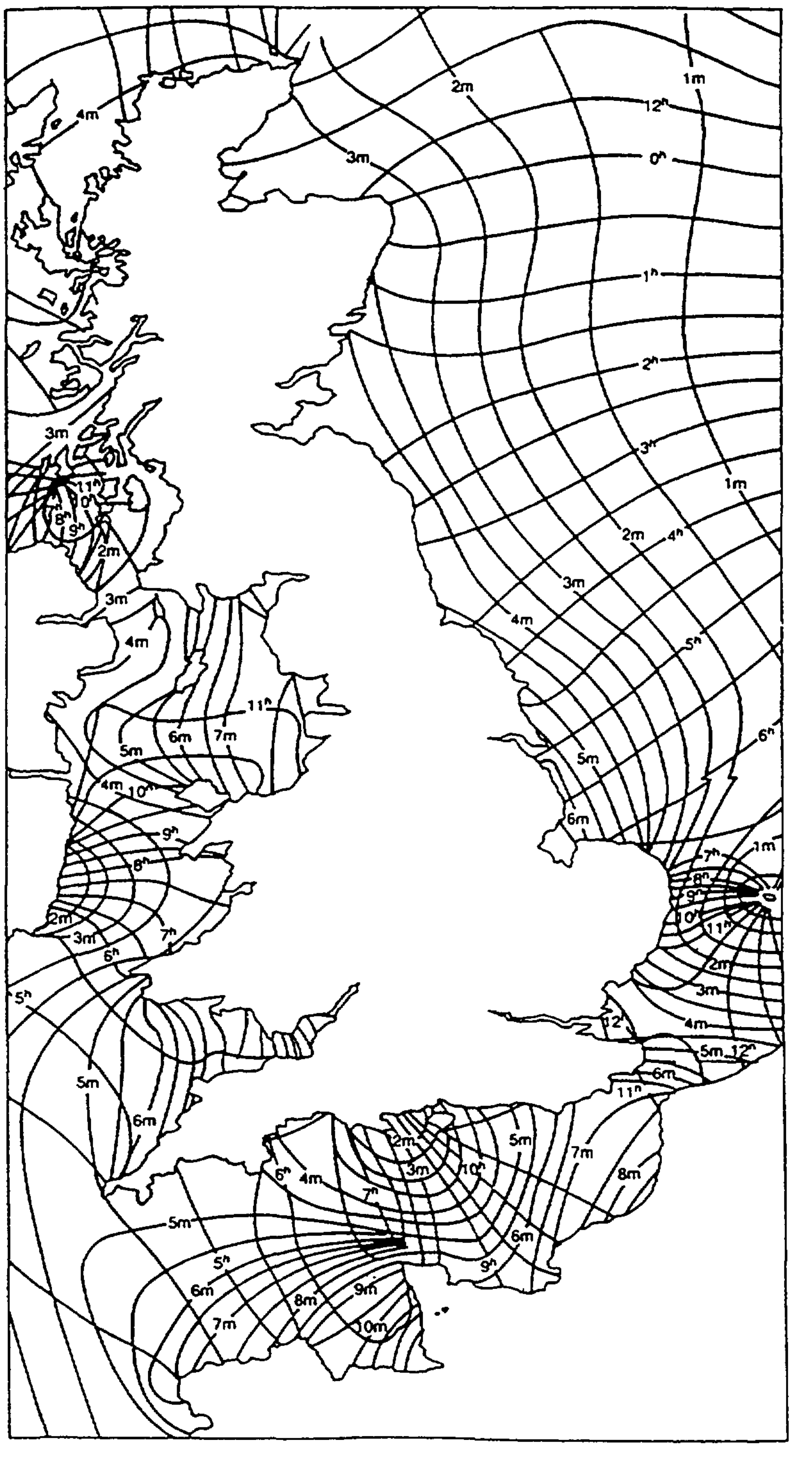

Fig. 1 Mean spring tidal rages around the United Kingdom.

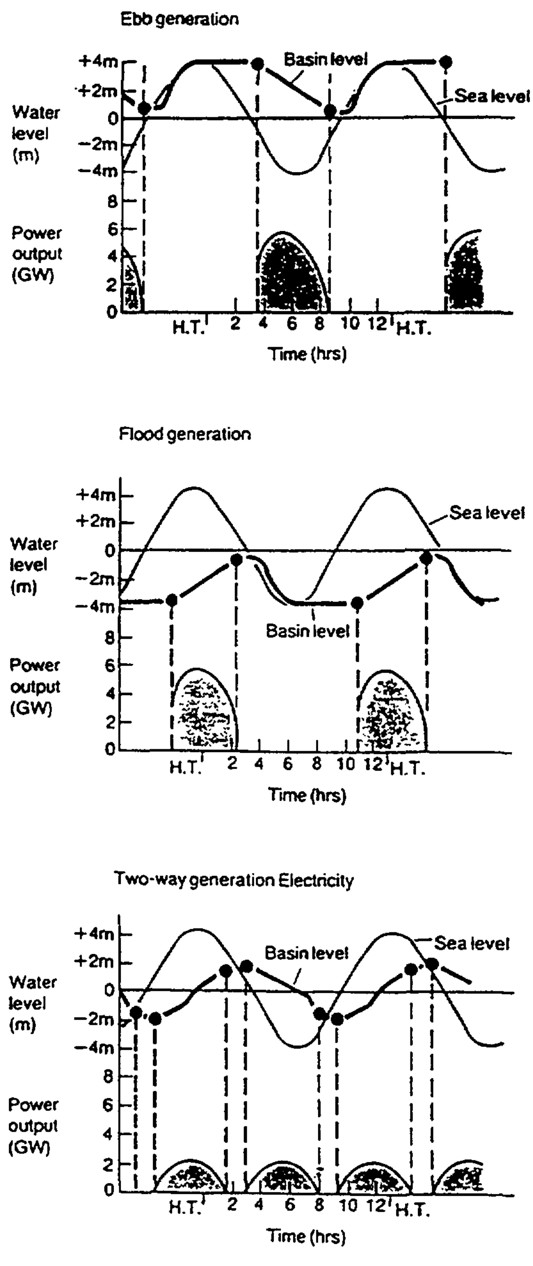

Fig. 2 Water levels and energy output for ebb, flood and two-way generation.

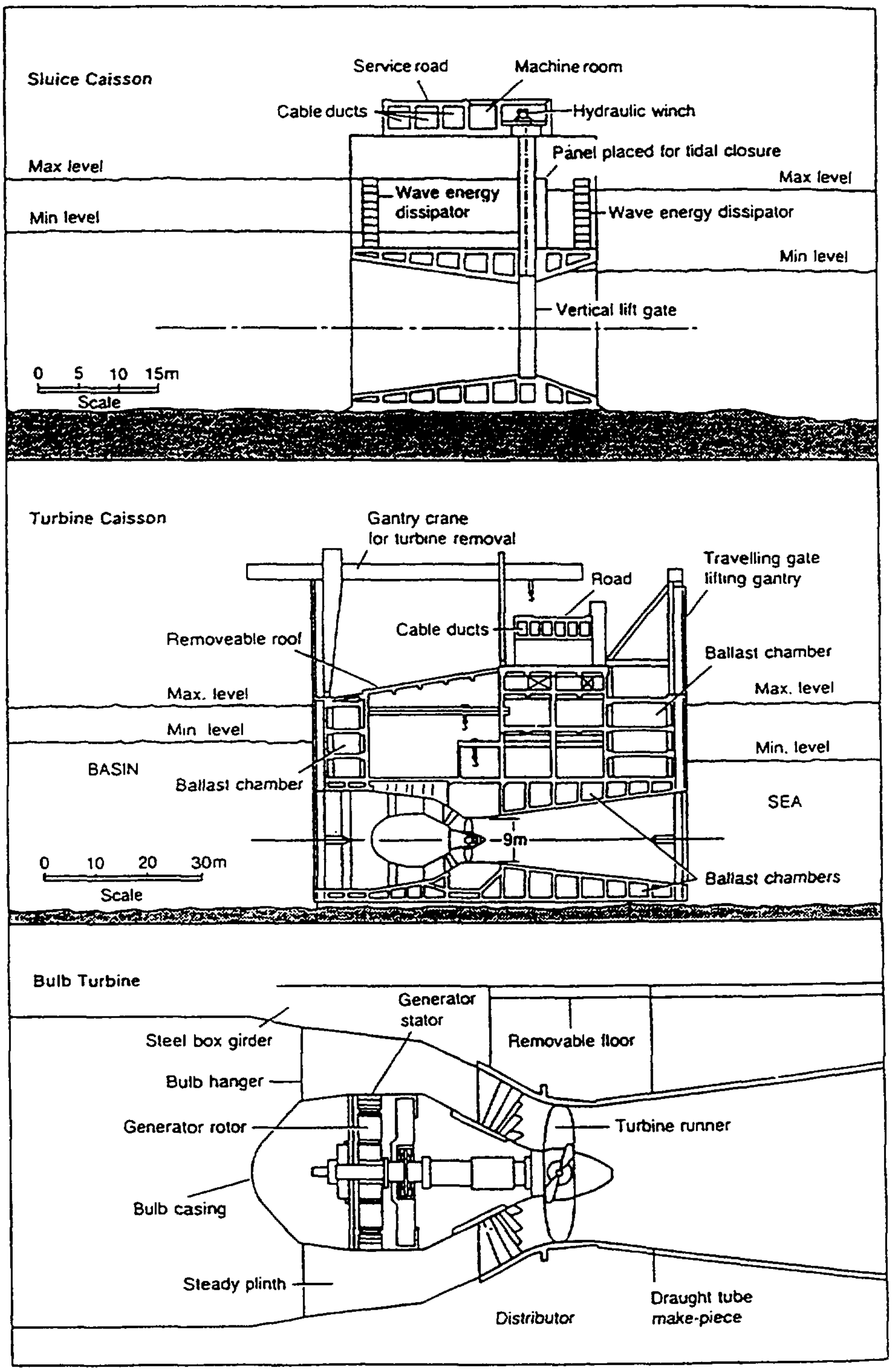

Fig. 3 Tidal power barrage designs.

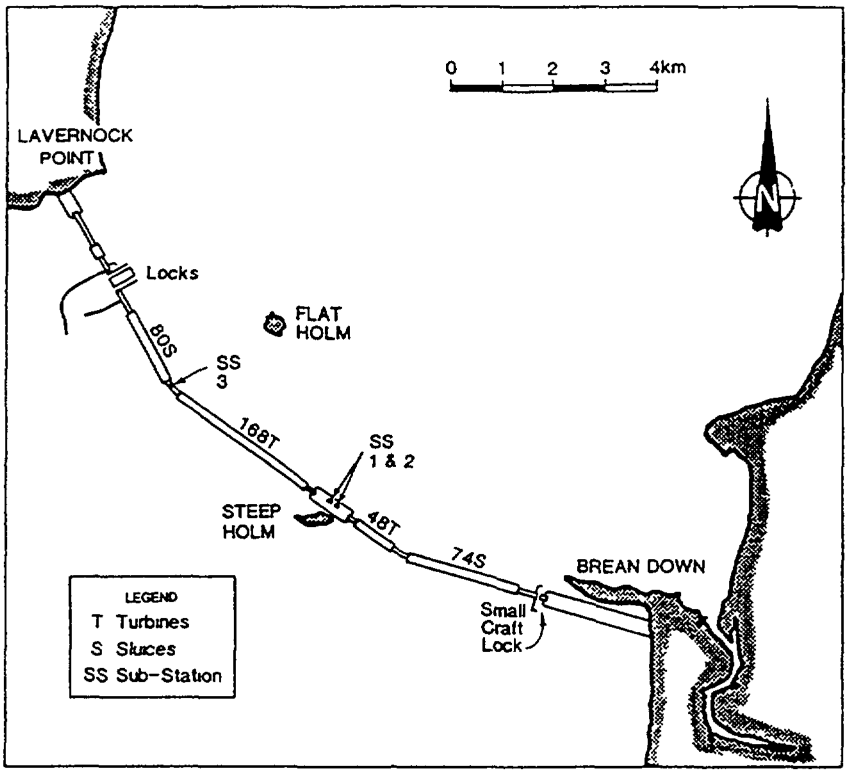

Fig. 4 Schematic of the Severn Barrage project, United Kingdom.

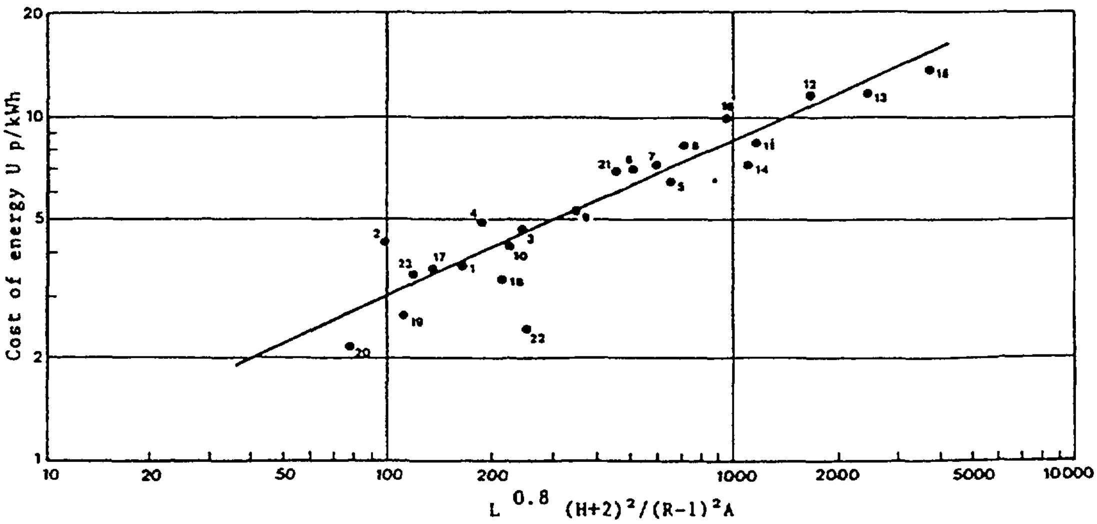

Fig. 5 Cost of energy plotted against the tidal energy cost function.

WAVE ENERGY

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ABSTRACT: This paper describes wave energy conversion systems as a technology for electricity generation. After a consideration of the nature of waves and the potential resource the paper discusses the technology, describing the basic principles, the conceptual designs and the proposed methods of operation and construction. The current status of wave energy world-wide is described and the leading projects noted. The final sections consider the environmental implications and economics of wave power.

1. INTRODUCTION

Wave energy is created when winds caused by solar energy interact with the surfaces of oceans. The largest concentration of wave energy on earth is between latitudes 40° and 60° in both the northern and southern hemispheres where the winds blow strongest. The obvious energy content of sea waves has long attracted inventors and numerous ideas for converting wave energy to a more suitable form of energy have been proposed in the past but none was sufficiently attractive to warrant development to the exploitation stage as long as fossil fuels remained cheap and plentiful. Within the last fifteen years, however, the realization that the era of cheap energy might be over has given fresh impetus to the study of renewable sources of energy, among them wave. There are literally hundreds of designs for wave energy conversion devices, many of these employ technology which is novel, either in application or design, and have not been proven. However, several devices have undergone sea trials and prototype devices have been built in Norway and the UK.

2. ENERGY RESOURCES AND RESERVES

2.1 The Nature of Waves

Waves at sea are primarily caused by the interaction of winds with the sea surface. They represent a transfer of energy from the wind to the sea and the energy in a wave is a function of the amount of water displaced from the mean sea level. The energy transferred depends on the wind speed, the distance over which it interacts with the water and the duration for which it blows. Prevailing westerly winds blowing for long distances over the Atlantic ocean can generate waves tens of meters high with over a hundred meters between crests and many tonnes of water displaced in each wave. The west coasts of the United Kingdom and the United States and the south coast of New Zealand have particularly suitable wave regimes for wave energy conversion.

Waves travel with velocities which depend on their wavelength - the longer the wavelength, the faster a wave travels - and in a real sea longer wavelength components move to the front; Fig. 1. This effect is seen in hurricane areas where long waves generally travel faster than the storm generating them and a hurricane is often preceded by heavy surf on beaches. Waves once formed will continue to travel in the direction of their formation after the wind dies down and even in a glassy calm the sea can be observed heaving in a long swell, probably caused by a storm which may have occurred days before and thousands of kilometers distant. In deep water, waves lose energy mainly by interacting with the atmosphere but long smooth swells can persist for hundreds of kilometers; shorter, steeper seas rapidly reduce to less steep ones.

The power of a wave is defined as the rate at which its energy is transferred across a one meter line at right angles to the wave direction and its expressed in units of kilowatts per meter of wavefront. It is customary to talk in terms of the mean annual power in the waves. The power in a wave train remains relatively constant in deep water. In water shallower than about half a wavelength, the oscillating motion of water particles near the bottom becomes appreciable and there are energy losses due to friction with the sea-bed. As well as causing losses, a shelving sea-bed causes a reduction in wave speed and may also cause a change of wave direction if the wave fronts approach the sea-bed obliquely. This latter effect occurs as the wave front is progressively slowed down, swinging it more parallel to the beach - a phenomenon readily observed in nature. If the sea-bed contours are irregular, focussing or de-focussing of waves can occur. The power at any specific coastal site may also be reduced by the presence of land masses which prevent waves from particular directions reaching the site.

There have been several attempts to quantify the size of the world's wave energy resource. Figure 2 gives an indication of the world-wide resource, giving the distribution of wave power levels, kW/m.

3. TECHNOLOGIES FOR ELECTRICITY GENERATION

The following discussion, although applicable to both onshore and offshore on wave technology, is primarily concerned with offshore wave energy devices intended for grid connection. The special case of small onshore wave devices is discussed at the end of this section. The technical characteristics of a scheme will necessarily be both design and site specific but the following table indicates the range in which some of the key characteristics may be expected to lie.

Unit Size	100 kW_e - 20 MW_e (scheme size potentially much larger)
Lifetime	20-30 years
Availability	70-90%
Load Factor	10-40%
Construction Time	2-5 years (for a nominal 2 GW_e scheme)

3.1 Principles of Wave Energy Convertors

The basic requirement of a wave energy convertor is that it should extract energy from the sea and convert it into an alternative form - usually fluid pressure or mechanical motion. This is done at the 'primary interface' where the convertor reacts to the motions of the sea to produce useful energy. The conversion of this energy to electricity is a particularly difficult problem because the low frequency of the waves (around 0.1 Hz) must be 'geared up' to the rotating speed of conventional mechanical and electrical plant.

3.1.1 Simple Device Concepts

There are several ways that convertors can interact with the sea. Some simple concepts are shown in Fig. 3 and include:

- tethered buoyant structures at or near the surface of the sea which would, if unrestrained, perform circular orbits
- surface followers; hinged structures which follow the contours of the waves
- structures in which wave pressure pumps air enclosed by a flexible element
- structures with an enclosed column of water acting as a piston to pump air. These structures can float or be fixed at, or below, the sea surface
- focussing devices using appropriately shaped conduits or chambers to increase wave amplitude.

3.1.2 Frame of Reference

In interfacing with the waves, any convertor must be constrained so that wave forces are resisted; this gives rise to the concept of a 'frame of reference' against which the convertor reacts. A frame of reference can be achieved in a number of ways, for example by:

- using the sea-bed for fixing or mooring
- mounting several convertors on a common frame or spine so that relative motion is obtained between them
- using the inertial force due to the gyroscopic action of a flywheel
- relying on the mass and inertia of the system

3.1.3 Device Orientation

When several convertors are mounted on a spine, the obvious way to orientate the spine is normal to the principal wave direction so that the maximum available energy is intercepted; Fig. 4. This orientation is defined as the 'terminator' mode because energy is absorbed by terminating the waves. In this mode the device intercepts energy in a wave front which has length equal to the length of the convertor (or group of convertors).

When a convertor in the terminator mode is constrained in heavy seas, considerable wave forces are exerted on its structure. One way to reduce these forces would be to re-orientate the convertor parallel to the principal wave direction so that a much smaller length of wave front would then be incident upon it and it would ride the waves rather like a ship does. In this orientation, energy capture could be expected to much reduced but, in practice, as energy is extracted from the sea at the head of the spine, the wave front diffracts into the sides of the spine and energy is progressively absorbed there. This orientation is known as the 'attenuator' mode. Convertors can be mounted on both sides of a spine.

The point absorber is a special category of device which is neither a terminator nor an attenuator. Its linear dimensions are small compared with those of the waves and although it is capable of capturing energy equally from all directions, its size prevents it from capturing the energy in large waves.

3.1.4 Size of Devices

The dimensions of a converter depend on the sea characteristics in which it is planned to operate. The designer usually attempts to tune the system by arranging that the natural oscillating periods of the converter match the periods of the most powerful waves; this is a complex problem.

Wave length is the most powerful indicator of device dimension. The crudest designs have dimensions about 1/4 wavelength and the better ones can be as small as 1/25. For a typical sea off Western Scotland, where the power carrying components are waves with heights around 3 m and wavelengths around 100 m, the calculation gives a range of linear dimensions for a converter from 4-25 m.

In the case of devices comprising several converters mounted on a frame of reference in the form of a rigid floating spine, the minimum length of the spine is determined by the need to ensure that the spine would always straddle at least two wave crests, thus reducing pitching motion. The maximum length is determined by the strength of the spine structure and, in general, is limited to about twice the wavelength. A rigid spine length would therefore typically be 200 m and this would allow approximately 10 converters to be mounted on it to form a single device.

3.2 Arrays

Many devices would need to be deployed if appreciable quantities of electricity were to be generated. The requirement of collecting and transmitting power mean that ideally the devices should be geographically close together.

Several problems would arise, however, if the devices were arranged in rows or too closely together:

- shadowing by devices in the front rows would cut off most of the incident energy from those in the rear unless there were a considerable fetch between rows;
- reflection of waves by a device could affect the power available at adjacent devices;
- the response of each device would be dependent on the incident direction of the waves and even if large gaps were left in each row to allow sufficient power to reach devices in the rear, changes in the sea's directionality could result in loss of efficiency.

Because each of these problems would cause loss of energy, the most efficient array of devices in a wave power station is likely to be a single row.

3.3 Wave Energy Converter Structures

In most cases the structure is likely to be the largest single cost center of a device and it would contribute some 30-40% to the capital cost of a wave power station. The structure would have a number of functions to perform, usually simultaneously. These could include providing buoyancy and inertia, resisting wave and other loads, enclosing converter chambers and acting as the working interface with the waves. Pneumatic device structures would need to contain large reservoirs or a series of air chambers, wholly or partly submerged, with surfaces subjected to hydrostatic pressure. If the structure was bottom-mounted the structure would either need to be designed to resist floating or require ground anchorage. Floating structures designed to span wave crests would function as heavily loaded beams, with bending forces alternating between tension and compression. Structures of floating devices which would rely on inertia as the reference frame would also need to be heavily ballasted.

3.4 Loads on a Wave Energy Structure

Design loads are governed by the need for the structure to survive in seas which could have maximum or storm energy levels much greater than the seas they would normally work in. The structure would need to withstand a wide variety of loads which could be broadly grouped into the following categories:

- Static (gravity) loads: structure mass; fixed equipment; ballast; stored liquids; buoyancy in calm seas.
- Dynamic loads: environmental (from waves, currents, wind, ice etc.); operational (from hydrostatic pressures, moving machinery, helicopters and service vessels etc.); temporary (from installation, towing launching etc.).
- Deformation loads: prestress; shrinkage and expansion; creep; temperature variations.

As well as loading other factors have to be considered; these include, fatigue, corrosion and stability.

3.4.1 Materials for Structures

Concrete is so suitable for meeting each of the requirements listed above that no really serious alternative to it has been considered for the large devices. It is by far the easiest and cheapest material for producing structures with high loading over large surface areas, it provides mass relatively cheaply and it can be formed in complicated sections with a consistent quality. Its low tensile strength is overcome by the use of reinforcement or by prestressing, whilst its compressive strength is high enough to result in very economical compression sections. Some devices would use steel for large components and there is confidence that adequate fatigue and corrosion lives could be achieved for them.

3.4.2 Structure Design

Steel ships and (to a lesser extent) concrete structures similar in size to wave energy devices have been designed and built, but the guidance notes and codes in existence have proved to have limited applicability to device design. The lack of existing design data is not surprising when contrasting the use of concrete in wave energy with the use of steel in ships and offshore structures. Ships are required to propel their mass through the water so the emphasis is on low weight in contrast to wave energy where the structures are necessarily heavy. Offshore structures are designed to be as transparent as possible to waves but wave energy devices must interact with the waves and present large surfaces to them.

3.5 Mooring and Anchoring

The ultimate safety and survivability of a wave energy device would depend upon the integrity of either the mooring system, if the device were floating, or the method of sea-bed attachment if the device were bottom-standing. Mooring principles have remained substantially unchanged for hundreds of years. Even though in the last decade or two the offshore oil industry has created the need for improved mooring systems with greater efficiency, durability and holding power, the technology of mooring has changed very little. The traditional chain and anchor remains the most effective mooring system for ships despite the dramatic increase in their sizes, but is unlikely to be suitable for the mooring of wave energy devices.

Among the factors which must be taken into account in considering wave energy mooring systems and which make them unlike those used at present are:

- the location of wave power stations in powerful wave regimes and generally in water depths up to 100 meters;
- the large number of structures required to be installed and the ability to spread the cost of expensive specialist equipment over the whole system;
- the permanence of the moorings, demanding reliability of a much higher order than previously achieved.

Contemporary mooring systems do not have the high reliability necessary to ensure continuity of electricity generation by devices. It is only on relatively small devices, such as navigation buoys and lightships, that a degree of permanence has been achieved. Even so, the life of such moorings is still appreciably less than the required life of a wave power station and permanence is achieved only by frequent maintenance and replacement. The total mooring force on a wave energy device could be comparable with the force on a large semi-submersible drilling rig. However, unlike the rig which can weigh anchor and move off-station to ride out storms, the wave energy device must remain on-station and survive the worst storms.

Very different approaches have been adopted by the various mooring designers since the performance of moorings would have to be compatible with the device operation. The different types of designs fall into three broad categories: tension leg, multi-point, single point. Tension leg mooring is a relatively recent development which is based upon the simple concept of using a taut mooring line or rope to connect the moored structure to a heavy weight on the sea-bed. The mooring line (or rode as it is usually termed) is, maintained under tension at all times by the buoyancy of the tethered vessel, with the object of maintaining it in a relatively fixed position. In practical systems the heavy weight on the sea-bed is replaced by a fixed tethering point which permits some angular motion of the rode. Multi-point systems, as their name implies, would employ redundancy in the number of rodes used to moor a structure. A single-point mooring would allow a wave energy device a greater degree of freedom to orientate itself to the predominant wave direction. Devices located in shallower waters would not require the use of mooring rodes and the structure would be attached directly to the sea bed. This type of installation might require some degree of seabed levelling and preparation before installation, possibly involving rock cutting and dredging. The sea-bed conditions at the location determine the type of anchor which can be used in the mooring system.

In general, the cost of mooring and anchoring, or the provision of sea-bed attachment, together with the cost of the initial device installation would be a significant fraction of the overall capital costs. It could range from 10 - 15% for floating devices, and could be as high as 30% for devices fixed to the sea-bed. The latter systems would be virtually maintenance free whereas moorings require periodic inspection and replacement, thereby incurring an operational cost penalty. Wave device designers are well aware of the problems of mooring and a number of solutions have been proposed to overcome them.

3.6 Power Conversion and Transmission

In order to be of practical use, wave energy captured by devices must be converted to a form of energy suitable for transmission to consumers. Possible schemes include conversion to chemical energy (battery storage or hydrogen production) and thermal energy (hot water) but conversion to electricity is the most attractive.

The energy density in waves means that the power conversion equipment of even the largest individual device may have a rating of less than 10 MW_e and a more typical rating would be 1 MW_e. The requirement for a large number of small generators does not pose any significant technical problems but it could give rise to both capital and operating cost penalties. Most of the technical problems relating to power conversion are associated with the primary interface of the device. Here the power plant has to meet two, sometimes conflicting, requirements:

- to provide the correct loading at the primary interface in order to enhance the device response, and hence power capture, over a wide range of sea conditions
- to convert the captured power to electricity as efficiently as possible.

Conventional electrical generators normally operate at a high, constant rotational speed producing power at the Grid frequency whereas the motion at the primary interface of a wave energy converter would be variable and only of the order of 0.1 Hz. Thus the power conversion system would need to combine an element of stepping up the frequency with power smoothing in order to provide a satisfactory link between the sea and the Grid. The power conversion problem is common to all devices and can be tackled in a variety of ways which can be classified under three main headings: pneumatic systems, hydraulic systems, mechanical systems.

In principle, any system could be used with any device concept, but in practice some devices would be most suited to one particular power conversion arrangement.

3.7 Pneumatic Systems

In a converter using a pneumatic power conversion system, the motion of the primary interface would be used to pump an air volume, producing a variable, oscillating air flow at the converter outlet. The air circuit may be open, drawing in from and exhausting to the atmosphere, or closed with a number of converters connected to a manifold. In both cases the low velocity air flow would be forced through a convergent duct to produce a high velocity air flow which could drive a turbine-generator. The variable oscillating air flow presents a problem to the turbine designer because a turbine is most efficient when operating in a steady air flow with a constant rotational speed. In order to maximize power conversion a turbine in a wave energy device must be operated at the highest possible efficiency at all times and if the air flow is variable its rotational speed would therefore vary. If a conventional air turbine was used to drive the electrical generator, the oscillating air flow would have to be rectified to give a unidirectional flow through the turbine. This could be done by the use of valves, either actuated by the air flow itself (passive valves) or actuated independently (active valves). The need for rectification valves could be eliminated by using a turbine which rotates in the same direction, irrespective of the direction of the air flow through it. The Wells turbine has such a characteristic and is also a high rotational speed machine, making it suitable for direct coupling to standard electrical generators. It is, however, not as efficient as more conventional turbines.

3.8 Hydraulic Systems

The simplest method employing liquid as the moving fluid in a turbine utilizes the difference in head between the crest and trough of the waves. The average head is less than 5 meters - somewhat lower than normally encountered in water turbines - consequently the turbines would be slow speed, large diameter, expensive machines. For this and other reasons, low head devices are unlikely to be cost-effective. Sea water could be pumped by the mechanical motion of devices, thus allowing a choice of operating pressures and the use of manifolding similar to the pneumatic arrangement above. Mechanical motion could also be used to pump oil rather than sea water. In such a system, a pump would be connected hydraulically to a motor which would, in turn, drive a generator.

3.9 Direct Mechanical Coupling

Direct mechanical coupling between the primary interface of a device and the power plant would be possible using one or more of several options including cranks, gears, cams, belts and friction drives. Whilst in theory it is possible to transmit the required torque levels with these options, they would be susceptible to wear caused by the onerous duty cycle imposed by wave motions.

3.10 Power Collection and Transmission

If power smoothing were introduced into the energy conversion chain it would limit the number and size of the power peaks to be handled by the electrical generator. This has cost advantages and allows the possibility of controlling the generator to permit constant frequency (synchronous) operation with conventional electrical coupling to the grid. In the majority of wave energy systems, however, it is believed to be more cost-effective to allow the generator to operate at variable frequency with an intermediate conversion stage provided to allow connection with the Grid. The most convenient buffer between the Grid and the variable frequency generated by a device would be a rectification/inversion arrangement. Such an arrangement would rectify the variable frequency AC to DC and then invert it back.

3.11 Availability and Maintenance

In any conventional power station the failure or malfunction of its component parts incurs a cost penalty associated with the necessary repair activity. This cost penalty has two components:

- the cost of the actual repair (men, spares etc.);
- the loss of revenue (i.e. energy) during the period that the station operates at reduced output.

In a wave energy station, carrying out repairs would be made more difficult by two features not normally found in conventional stations:

- the station would consist of a large number of relatively small generator sets, widely distributed;
- geographically access to the station would be limited by the weather because of its offshore location.

If a repair were delayed by the weather, the proportion of the year during which the station functions normally would be reduced. This proportion, formally termed the 'availability', is usually expressed as a percentage. For wave energy, however, this would not be a very useful measure because of the seasonal nature of the resource. The failure of components in the winter would be potentially more serious, in terms of lost energy, than in the summer. Thus in a wave energy station the term availability must be redefined as the annual energy delivered to the Grid (after allowance for component failure and seasonal effects) expressed as a percentage of the potential output of the station, assuming perfect operation.

High availability can be achieved only by reliable operation of the station or by having sufficient maintenance resources to be able to respond quickly to any failure, and hence minimize the amount of time plant is out of action. The maintenance resources consisting of men, ships and base facilities would have to cope with both the preventive activities such as inspection, servicing and overhaul, and with the unscheduled repair activities. The cost of maintenance could be minimized by organizing the teams to carry out preventive maintenance during the calm summer months, leaving the same teams free to do unscheduled repairs in the winter when more failures could be expected. The aim would be to keep a constant, but minimum, level of manpower employed throughout the year. In practice, however, there would always have to be some resources dedicated to repair activities throughout the year.

Maintenance costs would depend upon a number of factors and studies suggest the most important of these would be:

- whether a device is bottom standing or floating
- the maximum wave height at which access to a device would be possible
- the frequency with which overhauls must be carried out
- the number of devices for a given scheme capacity.

A further consideration for floating devices is whether the major on-board systems or components could be repaired at sea. The need to tow a complete device back to base for repair would significantly reduce availability unless provision is made for spare devices with which the faulty device could be exchanged. The cost of spare devices must be included in the compromise between a high availability and a low maintenance cost. Availability levels in the range 70-90% might be achieved.

3.12 Mean Annual Output of a Wave Power Station

Wave energy devices could not capture and deliver all of the power available to them in the sea. At each step in the power chain, from the interaction of the devices with the waves to the final connection of the on-land transmission line to the Grid, power losses would occur. Studies to date [1] have shown that the overall efficiency of wave power stations might be around 20%, although some concepts could theoretically achieve higher values. This is not surprising in view of the nature of the sea and the conflicting constraints it would place upon the operation of devices, thus limiting their efficiency. For most of the year they would be required to be effective power extractors over a wide range of wave heights and frequencies, yet during heavy sea conditions they would need to avoid efficient power capture in order to survive.

The factors which would influence the overall efficiency of the station power chain include:

- the directionality of the sea;
- the capture efficiency of the device;
- the rating of the power plant;
- the efficiency and operating characteristics of the plant;
- the efficiency and operating characteristics of the power collection and transmission system.

The first step in the power chain is the interaction of a device with waves. The capture efficiency of a device is a function of wave period and is a maximum at a period determined mainly by the dimensions of the primary interface of the device. This is one reason why many device designs are of a similar size.

All devices face the same design problem of ensuring that peak capture efficiency would occur at a period close to the predominant wave period. The capture efficiency of devices is also a function of wave height. In order to survive the excessive power levels present during storm conditions, devices would be designed to operate with reduced capture efficiency at higher wave heights.

The power captured by a device would vary both seasonally and on a wave-to-wave basis. Under these circumstances the power plant would be under utilized if it was rated at the maximum power capture level of the device. Plant would therefore be rated lower than the capture capability of the device and incorporate a power limiting arrangement to prevent overloads on those occasions when an individual wave exceeded the plant rating. In sea states with low incident powers, the power plant would be required to operate well below its design rating and its efficiency would be low.

The rating of the power plant is therefore a compromise whereby the plant could handle a reasonable proportion of the power available in winter and yet retain a reasonable efficiency during part-load operation for most of the year. Studies of a number of device concepts suggest that the overall power plant efficiency, with its optimum rating, would be about 60-80%. To achieve this figure it would be necessary to rate the plant at 2-3 times the average power level captured by the device.

The final stage of the power chain includes: the aggregation of power from groups of devices; transmission of the aggregated power to shore; the on-shore aggregation of power for bulk transmission to the Grid overland transmission of power to the Grid. It is likely that the annual efficiency of this final stage of the power chain would be about 85-95% dependent on the location and type of power aggregation employed.

3.13 Load Factor

When comparing the performance of different devices or device systems in different wave climates, the mean annual power output is not a very convenient measure because, whilst it takes into account the availability, it does not take into account the utilization of the power plant. A more useful measure, which includes both factors, is the load factor or the mean annual power output expressed as a percentage of the power plant rating. The load factor of a wave power station would generally be in the range 10-40%. By comparison, the load factor of a modern coal-fired base-load station is of the order of 65%.

The load factor of a wave energy system could be increased by decreasing the power plant rating below the optimum for maximum energy extraction. This would allow the power plant to operate for a greater proportion of the year, which could be of benefit in some applications, but the mean annual power would be reduced with only a marginal saving in the capital cost of the system.

3.14 Onshore Wave Energy

Much of the above discussion is applicable to both offshore and onshore wave energy devices; however, there are characteristics specific to onshore wave energy devices.

When wave energy is discussed as a means of providing large-scale, grid connected, electricity generation the talk usually concentrates on offshore schemes, floating or fixed. Onshore wave energy, because of the lack of exploitable coastal sites and the lower wave power levels, is not really suitable for providing large amounts of electricity for distribution to a distant market. However, it is potentially suitable for providing a relatively small, MW level, amount to meet a local need. This is possibly an advantage as it can be targeted for markets where its competition, conventional fossil fuelled generation, is expensive - isolated island communities for example.

They can also be constructed considerably more quickly and economically than offshore devices using conventional techniques and without the requirement for special construction yards etc. Once built, access should be similar to that for a conventional power station and the costs of operation and maintenance considerably less than those for an offshore scheme. Although on average the onshore wave power levels may be an order of magnitude less than those offshore, the coastline and the topography of the sea bed will focus waves and enhance the power at certain locations. These sites can be exploited for power generation. The more favorable economics of onshore wave energy, its smaller-scale and identified market suggest that it has a more promising future than offshore wave energy in the short term.

3.15 Current Status of Wave Energy World-wide

3.15.1 Japan

Japan is probably the most active country in wave energy at the present time [2]. The annual average wave power levels around Japan are low, of the order of 10 kW/m contrasting with the North Atlantic where the levels may be greater than 50 kW/m. However, the high cost of imported coal and oil, the many islands that make up Japan, the low tidal range and the Japanese affinity with the sea have led to their interest in wave power.

There is a considerable amount of wave energy research being undertaken with many sea going trials. Devices which have been sea tested include:

- Kaiyo, a floating terminator
- Kaimei, a floating oscillating water column device
- Pendular, a pendulum gate swinging within a chamber;
- A Wave Power Extracting Caisson Breakwater
- The Backward Bent Duct Buoy
- An Inshore Oscillating Water Column Array
- An Onshore Oscillating Water Column

3.15.2 United Kingdom

The UK Department of Energy program of wave energy research and development began in 1974 and the program to mid-1990 has cost approximately £18M. Over three hundred ideas for capturing wave energy were examined. The most attractive concepts were tested at small scale in wave tanks, and three were tested in sea conditions at one-tenth scale. Eight devices were taken to the stage where reference designs for a 2 GW_e power station located off North West Scotland were produced and coasted. (Diagrams for two of the devices which were assessed are shown as examples of wave energy devices, Figs. 5 and 6.) The studies which were undertaken indicate that the technically achievable resource may be 6 GW_e. A prototype shore-mounted oscillating water column device has been built on the Scottish island of Islay with a nominal capacity of 80 kW_e and an anticipated annual energy delivery of 300 MWh [3]. This device is mounted over a gully which enhances the wave energy available. It started generating in early 1991 and will be connected to the islands electricity supply. Studies have also been commissioned to assess the shoreline and onshore wave energy resource for the UK. A review of the prospects for wave energy in the UK is currently being undertaken by the Department of Energy the results of which are expected in 1991.

3.15.3 Norway

Research work in Norway has concentrated on two wave energy devices, both onshore, the TAPCHAN and the Oscillating Water Column. The TAPCHAN [4] consists of a tapered channel into which waves enter. By virtue of the taper the waves are focussed and their crest height is increased. At the end of the channel water flows over the top into a reservoir and from there back to the sea via a turbine, the device is only suitable for coasts with a small tidal range. The Oscillating Water Column [5] has been developed by Kvaerner Brug. Their design consists of a cliff mounted hollow column the lower entrance of which is below the water surface. Water swell causes the water in the cylinder to rise and fall and in doing so to pump air through a Wells turbine. A prototype device has been built and was successfully operated before being destroyed in a storm. Both devices are intended for use on islands where conventional electricity generation, for example from diesel generators, is expensive. Neither the TAPCHAN nor the Kvaerner OWC have yet been built as commercial schemes.

3.15.4 Sweden

Sweden has a relatively modest wave energy research program. Device development has been largely confined to a study of a buoy device.

3.15.5 Portugal

Portugal is developing an Oscillating Water Column device with the intention of installing a 500 kW_e unit on Pico island in the Azores.

4. ENVIRONMENTAL ASPECTS OF ELECTRICITY GENERATION

4.1 Introduction

Wave energy would replace fossil fuels and have a positive influence on reducing harmful greenhouse gas emissions. The local environmental effects, some of which may be considered beneficial others detrimental, are necessarily dependent on the choice of site. These are discussed in more detail below.

4.2 Characteristics of Devices

Among the characteristics of wave stations which may have local environmental implications are:

- the areas of sheltered water they would create
- the attraction they would have for fish, sea-birds, seals and seaweed
- the effects they would have on tidal currents.

4.3 Coastal Effects

A wave power station would modify the local wave climate. Floating devices with low freeboard well out to sea would probably have little or no effect on the coastline but a station of bottom mounted devices might. A decrease in the wave energy incident upon shores and shallow sub-tidal areas could result in changes in the density and species of organisms they support.

4.4 Navigation of Ships

Wave energy devices could present a hazard to shipping because of their low freeboard which would render them relatively invisible either by sight or by radar. This could be minimized by clearly marking the devices and leaving navigation channels in the device arrays.

Wave energy devices drifting as a result of mooring failure would also present a navigation hazard, not only to ships but to coasts and harbors to landward of a station. Repair resources would need to be deployed sufficiently rapidly to retrieve them before they reached land. These techniques have been demonstrated by the offshore oil industry.

5. ECONOMICS OF ELECTRICITY GENERATION

The construction, assembly and installation of a large wave power station (GW scale), together with the necessary electrical interconnection, would be a considerable undertaking and require the total investment of several billion pounds. The power station would, however, be made up from self-contained groups of devices, which would allow the building of the station in stages and provision of energy before the construction was fully complete.

For costing purposes a wave power station may be divided into a number of 'cost centers':

- device structure;
- mechanical and electrical (M&E) plant;
- installation and mooring;
- power collection and transmission;
- operation and maintenance.

A report published by the UK Department of Energy in 1985 [1] describes the assessment of designs for nine different large-scale offshore wave energy devices and gives an indication of the possible distribution of costs between these centers. An illustration of the breakdown of costs between the identified cost centers is shown as Fig. 7.

The difference in wave energy regimes and the considerable variety of devices with varying costs and performances leads to a wide range of estimates for the cost of electricity from wave energy. These cost estimates are detailed in references [1-7].

6. CONCLUSIONS

Considerable research into wave energy has been undertaken in a number of countries over the last twenty years and numerous devices have been built and tested as prototypes with varying degrees of success. The research and development work that is being undertaken is now directed more towards small-scale, onshore or fixed applications which may have benefits for large-scale floating devices. Of the specific technologies for wave energy exploitation, terminators appear more favored than attenuators or point absorbers and the air coupled water column device, utilizing the Wells self-rectifying air turbine, appears the most favoured route to demonstrate the potential of wave energy at the present time.

Wave energy is still at the R&D stage and large-scale offshore wave energy is probably some way from the market. Small-scale onshore wave energy has reached the demonstration phase and has a potential market in locations where the cost of conventional generation is expensive.

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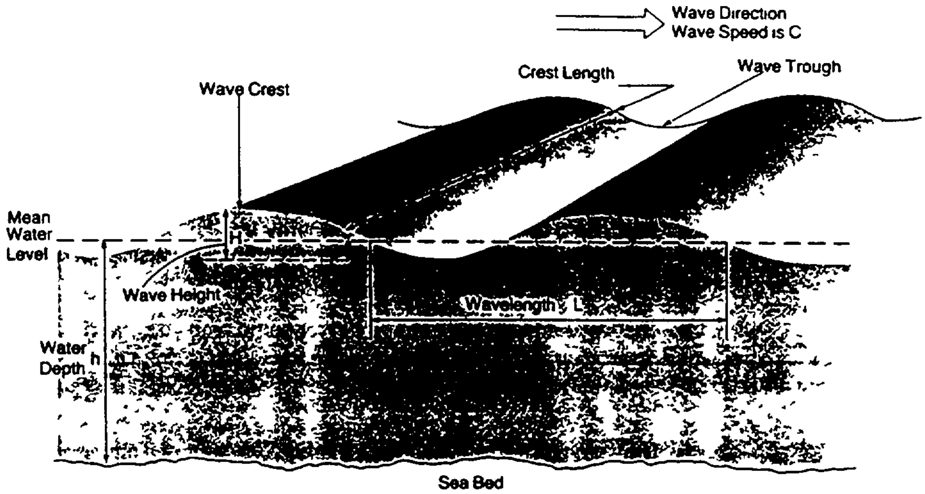
[8] Implementing Agreement for a Program of Research and Development on Water Power. Annex II, Volume 3, IEA

Fig. 1.1 An idealized wave.



Some Useful Equations

Wave period	$T = L/C$
In deep water	$L = gT^2/2\pi$ $C = gT/2\pi$
In shallow water	$L^2 \approx ghT^2$ $C^2 \approx gh$

Some Wave Dimensions

- Typical waves off South Uist have wavelengths in the range 50–250 m and wave heights in the range 1–6 m
- A wave of wavelength 150 m, period 10 seconds and height 3 m would have a power of 50 kW/m

Fig. 1.2 Particle orbits for different water depths.

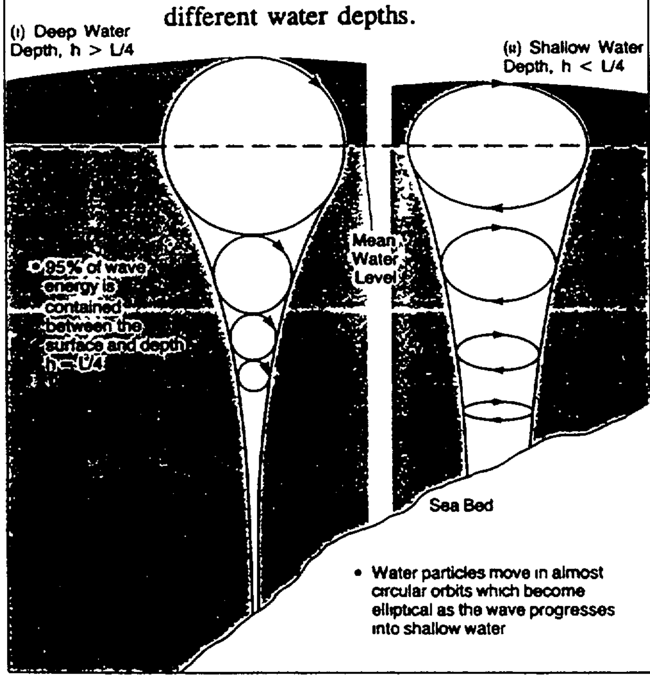
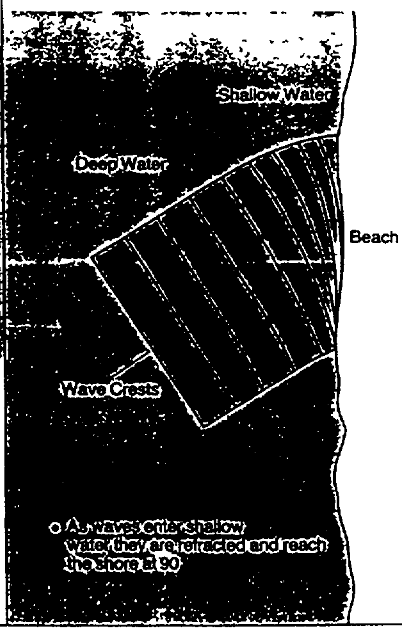


Fig. 1.3 Wave approaching a beach.



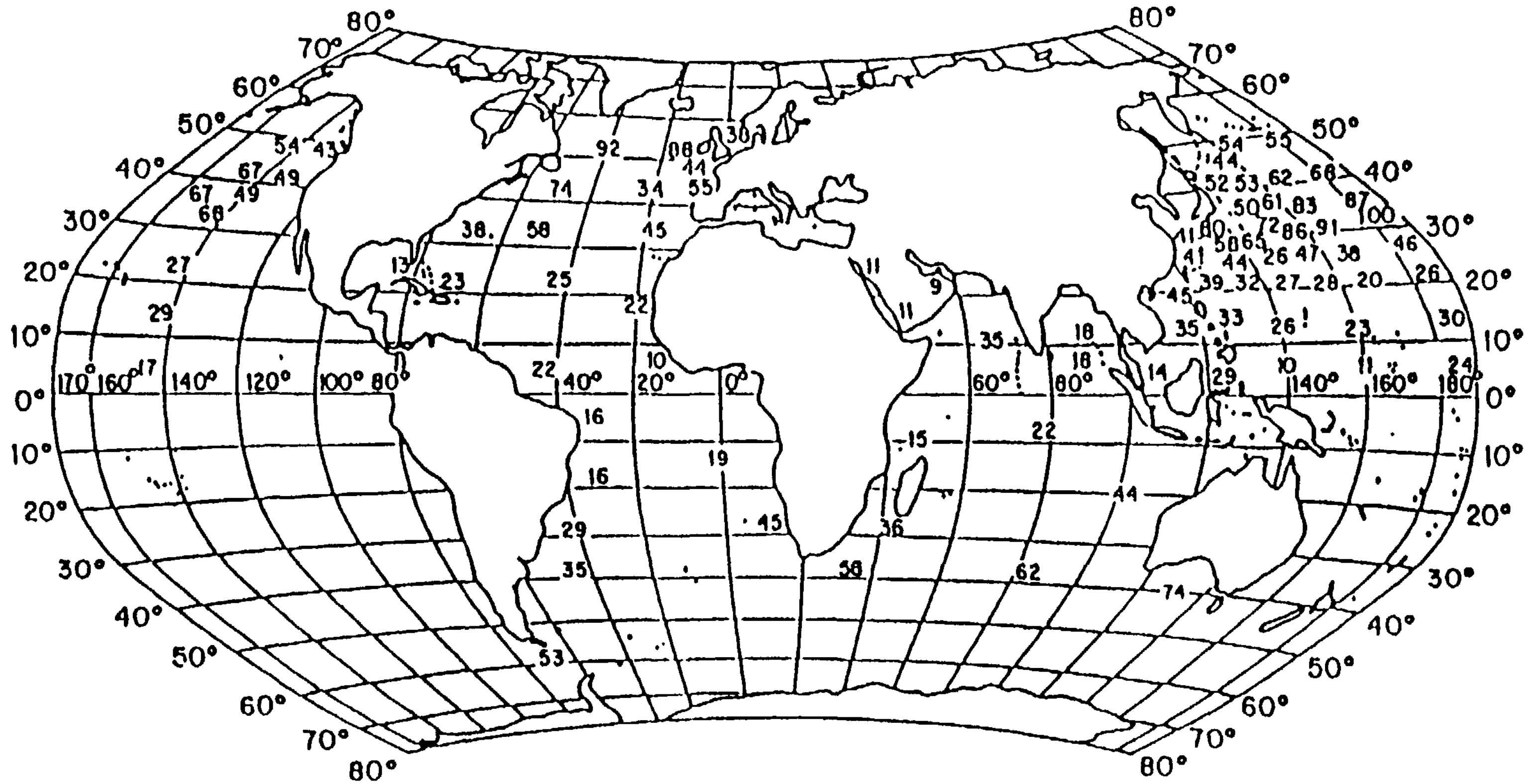


Fig. 2 Estimate of World-wide Distribution of Average Wave Power in kW/m.

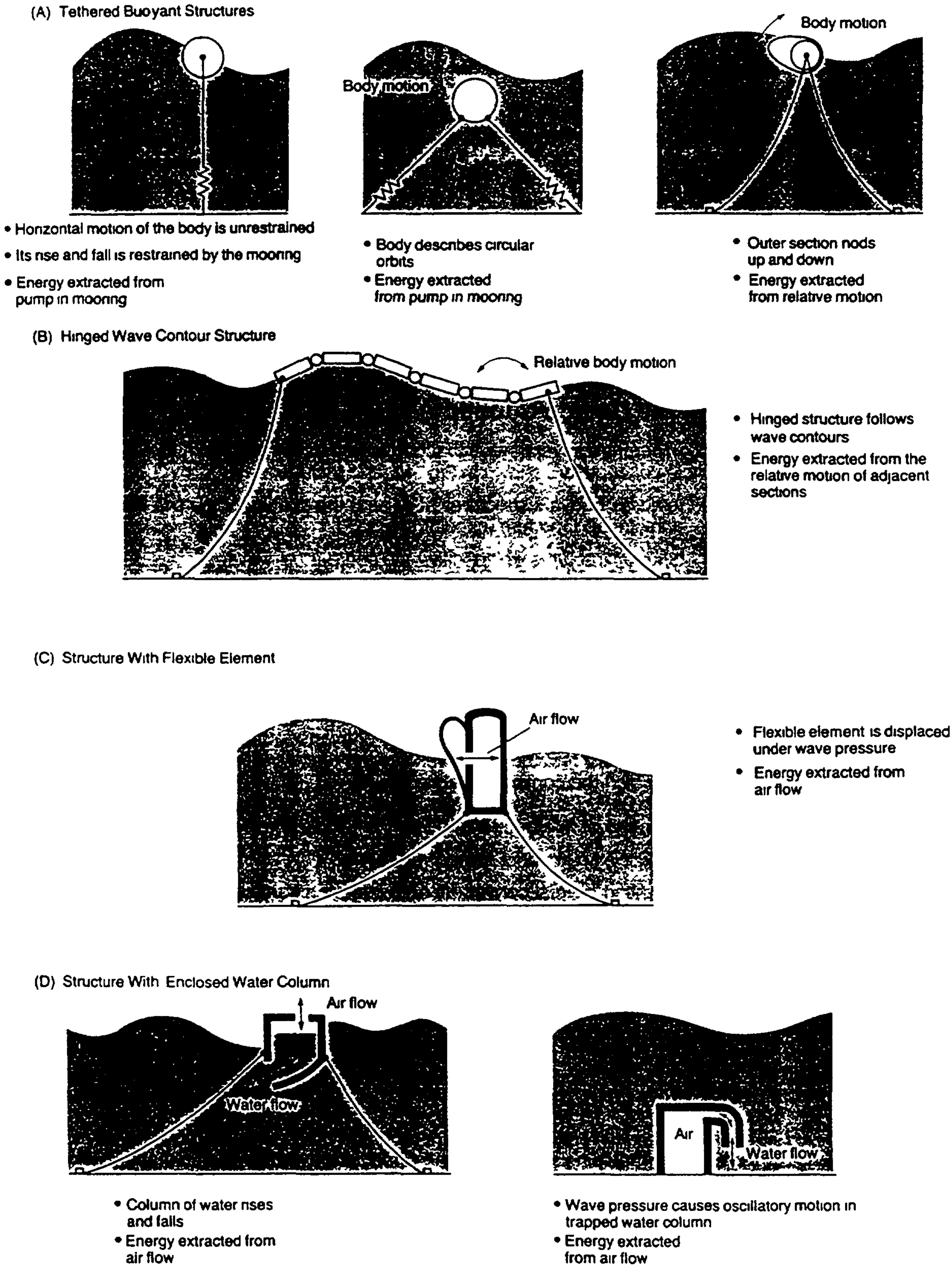


Fig. 3 Simple Device Concepts.

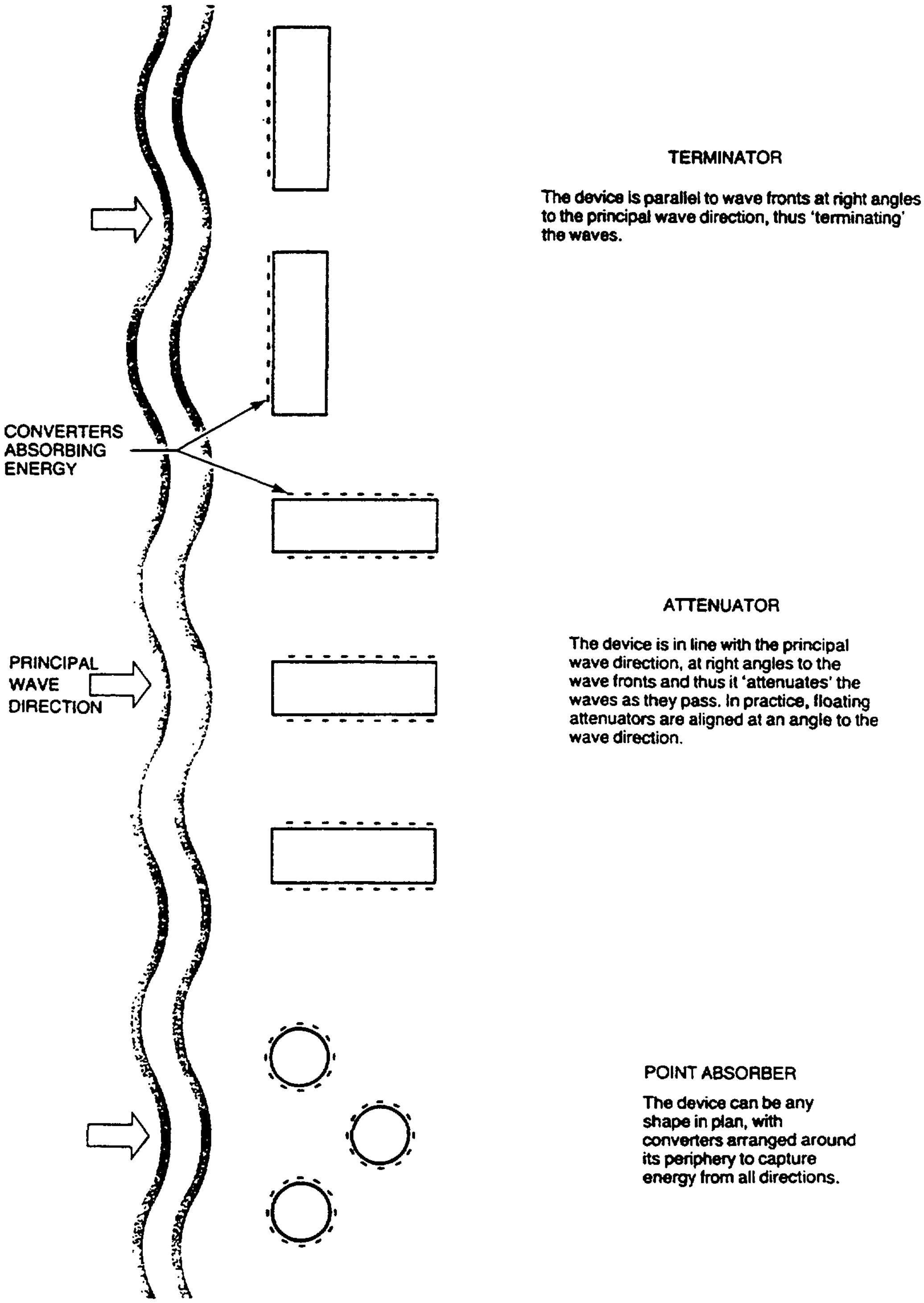
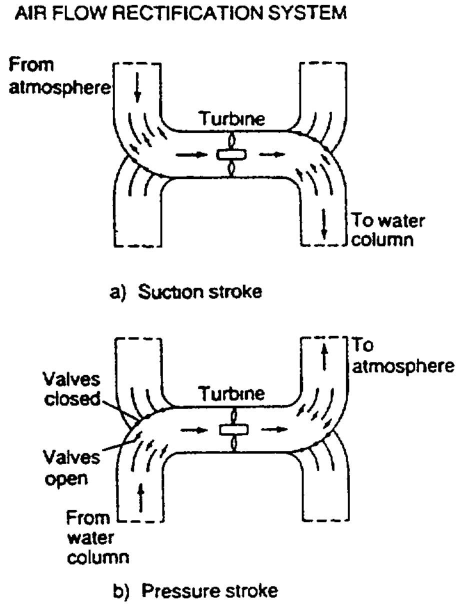
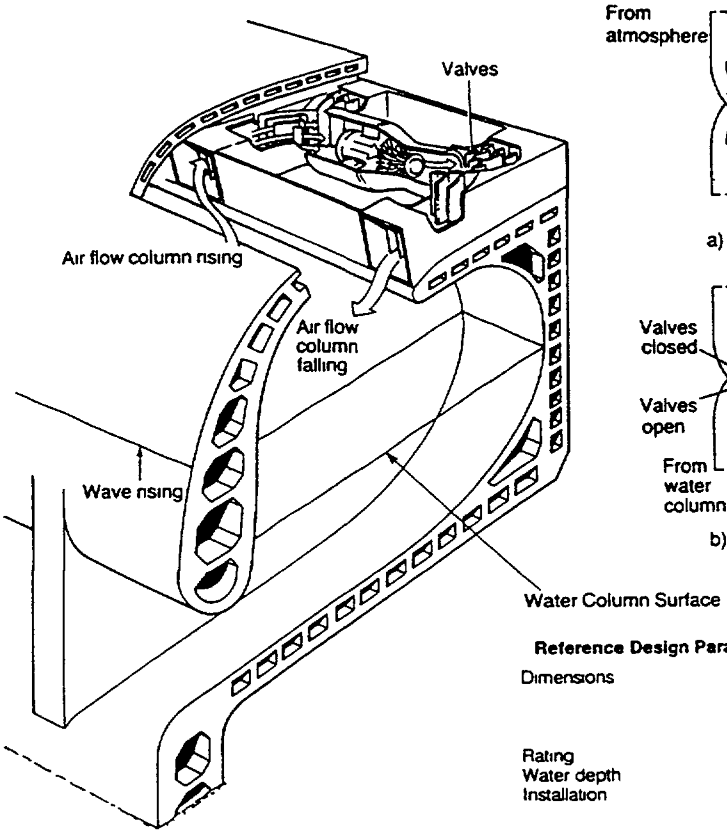


Fig. 4 Device Configuration.





Reference Design Parameters

Dimensions	length	64m
	width	32m
	height	34m
	weight	22 500 tonnes
Rating	4 7 MW	
Water depth	21m	
Installation	Bottom standing	

Fig. 5 NEL OWC (Bottom standing terminator).

Reference Design Parameters

Dimensions	Spine length	290m
	beam	13m
	depth	15m
	weight	45 000 tonnes
	Bag dimensions	25m x 13m
Rating	10 MW	
Water depth	80-100m	
Installation	Compliant moorings	

The moving wave collapses the bag This is then reflated as the wave falls Air is pumped through the turbine on both strokes

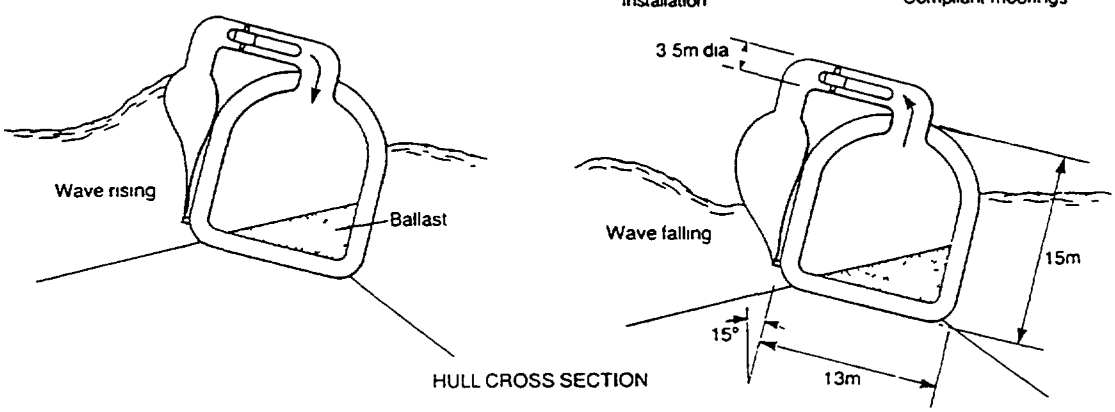


Fig. 6 SEA Clam.

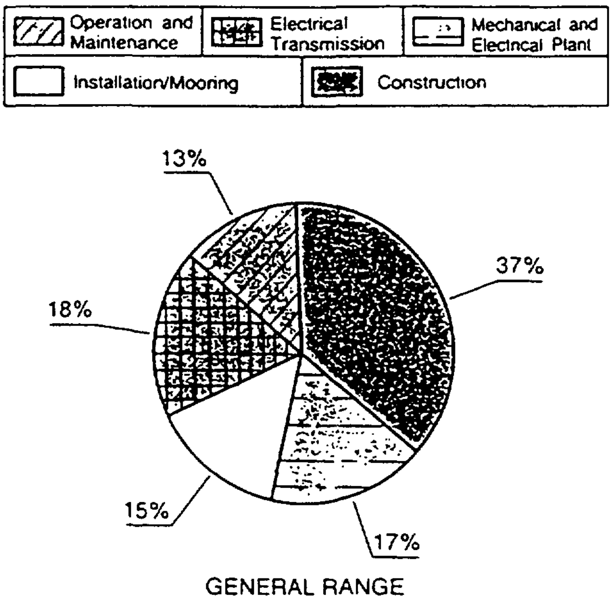


Fig. 7 Wave Energy Cost Breakdown.

NATURAL GAS

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Geneva

ABSTRACT: This paper reviews and discusses the resource base, both in terms of the short- and long-term and production prospects, by regions and select countries, for natural gas. Gas trade is identified and future prospects evaluated. Market developments for gas are reviewed, including environmental factors associated with the production, transmission, distribution and end-use of natural gas. The aim is to provide a basis on which natural gas could be evaluated against other sources of energy used in electric power generation.

1. INTRODUCTION

Natural gas is a relative newcomer in the world energy scene with a few exceptions, notably in the United States (USA). There, the industry began to develop as far back as the late 1920s. In the 1950s, however, the development of gas markets accelerated because of the availability of large volumes of gas as a result of oil exploration and rising demand for energy. Long-distance, high pressure transport of gas became possible through the development of gas pipeline technology. Gas enterprises were able to secure long-term financing to build the necessary infrastructure to deliver gas to consumers. Consumers also preferred natural gas to manufactured gas. It was clean, efficient and found a number of market outlets, in the domestic sectors, in electric power generation and industry, and as a feedstock for the petrochemical industry. It also became an important source of liquefied petroleum gases (LPG).

The USA experience in the development of a gas market served as a model for other countries which came to discover and develop their natural gas resources. In Europe, large supplies of natural gas became available which were within access to existing gas markets, many of which were based on manufactured gases. Gas enterprises adopted co-operative measures to develop integrated gas transport and distribution systems. They were able to secure public and private financing to engage in long-term contractual arrangements to buy and sell gas. Gas trade for producers provided an important source of foreign exchange earnings. Gas trade, which was limited to gas pipelines and regional in nature, began to develop worldwide in the 1960s through the use of special sea-going vessels, and liquefied natural gas (LNG) trade developed, making it possible to connect distant sources of gas supply to markets.

Two relatively recent events have favoured the further use of gas. The energy crisis of the early 1970s, caused a number of countries, concerned with their heavy dependency on oil, to adopt measures to diversify their energy supply mix, including an increased use of gas. A more recent development is the growing concern of the impact on the environment caused by the intense use of fossil fuels, namely coal, oil and natural gas. Both in qualitative and quantitative terms, natural gas is a much cleaner fuel, compared to oil and more so for coal.

In response to a growing demand for gas, world gas reserves and production have increased significantly, to the point that ample supplies are available. Natural gas currently provides about 20% of the world's primary energy consumption [1]; compared to about 38% for oil, 30% for coal, and the remainder, nuclear and hydro. Fossil fuels account for 88% (Fig. 1). This global perspective, when viewed regionally, provides a better insight on the variance that exist among these regions on energy supplies and related environmental problems arising from the dependency on these sources of energy.

For OECD member countries [2] (Fig. 2), which on the whole are the largest producers and consumers of energy and contribute the most to environmental degradation, primary energy consumption (p.e.c.) in 1987 consisted of 42.6% oil, 24.1% coal, 18.8% natural gas, 6.5% hydro and 8% nuclear. Fossil fuels accounted for 85.5%. In centrally-planned economies, p.e.c. (Fig. 3), consisted of 42.6% coal, 26.8% oil, 24.6% gas, 3.8% hydro and 2.2% nuclear. Fossil fuels accounted for 94%. In developing countries (Fig. 4), many of which are large producers of oil and gas, p.e.c. consisted of 52.6% oil, 19.7% coal, 16.6% gas, 9.4% hydro and 1.7% nuclear. Fossil fuels accounted for 92%. The dominance of fossil fuels is clear and will likely remain so for the foreseeable future. Given the relative lower market share for gas in many countries of these regions, there is room for further growth for gas.

Natural gas can be substituted for various end-uses served by oil products and coal, especially in traditional markets served by these two energy sources, such as industry, electric power generation and even in the transport sector. Because of its inherent physical and chemical properties, natural gas is an option which, coupled with other measures such as enhanced energy efficiency, greater use of new and renewable sources of energy and improved technology to make other sources of energy environmentally more acceptable, can appreciably improve the environment for countries willing to choose that path. Natural gas can serve as a transitional energy source into the next century for countries seeking to develop energy policies that bring into balance energy needs compatible with environmental objectives.

2. NATURAL GAS RESERVES AND RESOURCES

Extensive literature has been published on oil and gas resource assessments, which identify a wide variety of techniques for making resource estimates. Such estimates are subject to uncertainties and a great deal of judgement is required in making them. It is often said that making such estimates is as much an art as a science.

The world-wide occurrence of hydrocarbons, their varying reservoir conditions and characteristics, and the criteria employed for making estimates often lead to estimates that could change appreciably from year to year. This is more so in the case of estimating proven reserves. Estimates are often influenced by the purpose for which the estimates are made and by whom. Reserves for oil and gas producers are strategic assets, and it is not uncommon to underestimate or overestimate reserves for economic and/or political reasons. Making resource estimates is a dynamic process, since increased knowledge of the geological settings of where these resources exist, and reservoir performance during production, increase the reliability of such estimates. Estimates often include assumptions and definitions which are not clearly defined. Nonetheless, in countries with a long history of hydrocarbon exploration and production, estimates tend to be more precise than in countries where such activities have limited history. In comparing estimates from different sources, it is wise for an analyst to have a clear understanding of the methodology employed and definitions of terms. Some estimates may have depth limitations, others may have different economic and technical assumptions, some may exclude so-called "unconventional" gas sources. In some cases, reserves which are not accessible to markets may be excluded. Resource estimates generally take two approaches. A geological approach relies on information and assumptions about the physical nature of the resource itself, taking into account the volume of sedimentary rocks likely to have hydrocarbons, the number of geological structures, presence of "source" rocks, etc. The historical approach, on the other hand, relies on evaluation and extrapolation of trends of production, reserve additions, discovery rates, wells drilled, etc. This approach relies heavily on historical records.

One organization which over the years has been involved with the development of classification and nomenclature of oil and gas resources is the World Petroleum Congress (WPC), which seeks as one of its objectives international standardization in this field. One of the contributions of the WPC in this field is that it periodically prepares world-wide estimates of hydrocarbons. These estimates, done by a team of international specialists, reflect consistency over time, and provide a good world-wide perspective of factors that influence the estimating process. The most recent estimates by the WPC were prepared for the WPC held in 1987 [3]. A brief overview of the results of this report is noted below. Since this assessment had a cut-off date of January 1985 and excludes "unconventional" gas, an update is given in this report on proven reserves, as well as information on "unconventional" gas.

2.1. Proven Natural Gas Resources

Proven reserves or identified reserves, a term used by the WPC, consist of quantities of gas which the analysis of the geological and engineering data demonstrates with reasonable certainty to be recoverable under economic and operational conditions at the time the estimates are made. It is a definition generally accepted by most estimators.

Original reserves of gas, as of 1 January 1985, and their component parts - Identified Reserves and Cumulative Production - are shown for the world and by regions in Fig. 5 and Table I. The distribution of these reserves is quite narrow, with 32.6% located in the USSR, 30.4% in the Middle East and 12.8% in North America. This distribution reflects in large measure the influence of the more intense and wide-spread oil exploration over natural gas. Another important indicator of the production potential is the Reserve-to-Production Ratio (R/P). In 1985, it was 840 for the Middle East, 65 for the USSR and 22 for North America. The distributions of these reserves indicate the extent of under-utilization of reserves relative to gas markets, as in the case of the Middle East. It is also a generally accepted view that proven reserves of natural gas often tend to be understated, since the delineation of gas reserves is much less precise than that of crude oil. There has been significantly greater exploration and production associated with crude oil than for natural gas.

Table I World estimates of original reserves and ultimate recoverable resources of conventional gas

Unit: 10^{12} ft^3	Cumulative production	Identified reserves	Original reserves	1984 prod.	R/P	Undiscovered resources	
						95%	5%
NORTH AMERICA	20.05	14.14	34.05	0.65	22	12.68	38.64
SOUTH AMERICA	0.75	3.50	4.25	0.05	70	2.32	11.22
EUROPE	3.72	8.42	12.14	0.24	35	2.64	8.53
West. Europe	2.67	7.63	10.30	0.18	42	2.64	8.53
East. Europe (excl. USSR)	1.05	0.79	1.84	0.06	13	-	-
USSR	6.63	36.13	42.76	0.55	65	20.93	81.05
AFRICA	0.35	6.65	7.00	0.05	133	5.64	23.31
MIDDLE EAST	0.65	33.62	34.28	0.04	840	18.27	52.58
ASIA/OCEANIA	1.08	8.14	9.22	0.08	101	9.46	36.35
WORLD	33.23	110.71	143.94	1.67	66	75.08	243.37

Proven reserves of natural gas fall into two categories: associated/dissolved gas and non-associated gas (Annex I). The former tend to be rich in hydrocarbons (the WPC report estimated that the natural gas liquids reserves were in the order of 58.6 billion barrels, of which 30.3% were in the Middle East and 32.5% in the USSR), and have certain limitations in their availability to gas markets. Their production is influenced by oil output. They may be reinjected for enhanced oil recovery or at places flared or vented. Non-associated reserves, on the other hand, have no such production restrictions. Their availability tend to favour gas markets that need long-term, steady and reliable rates of production. The world-wide distribution of these two categories of gas generally reflects the historical development and production of crude oil, where the presence of associated/dissolved gas is high, as in the Middle East, whereas in the developed gas markets of Europe and North America, non-associated gas is prominent. Figure 6 provides a relative worldwide distribution of these two types of natural gas [4].

A more recent assessment of proven reserves reinforces the trends of recent decades, showing constant rates of increase relative to production. As of 1 January 1989, proven reserves worldwide were 116.3×10^{12} m^3 [5] (Fig. 7, Table II) and the R/P ratio was about 60. Regionally, they were concentrated in the Soviet Union, with 42.5×10^{12} m^3 (36.5% of the world's total and an R/P ratio of 55); and Asia, with reserves of 42.5×10^{12} m^3 (36.6% and an R/P of 200), whereas the relationship of these reserves to large developed gas markets is significantly less, as in the case of Western Europe and North America. Indicative of the worldwide market status of world-proven reserves is work done by Jensen Associates. Jensen periodically reviews the world's inventory of reserves to ascertain the exportable surpluses (i.e. reserves uncommitted to markets) sufficient in size to support base load export markets or large domestic needs. As of 31 December 1987, Jensen estimated the surplus to be in the order of 47×10^9 m^3, or 43% of the estimated reserves (Fig. 8 and Table III) with the largest surpluses being in the Soviet Union, Iran, Abu Dhabi, Qatar and Algeria. These surpluses take into account long-term supplies already committed to markets, as in the case of Western Europe and North America, where only few countries of these regions have a surplus, as with Mexico, the Netherlands and Norway.

Table IIa World natural gas proven reserves, marketed production and consumption

Unit 10^9 m^3	Proved reserves at year's end		Marketed production		Consumption	
	1987	1988	1987	1988	1987	1988
WESTERN EUROPE	5,512	5,427	199 33	187 78	268 88	259 36
Austria	12	13	1 17	1 26	5 28	5 14
Belgium	-	-	-	-	9 44	8 64
Denmark	123	120	2 43	2 39	1 67	1 56
Finland	-	-	-	-	1 58	1 62
France	33	30	3 83	3 17	30 75	28 52
Germany FR	189	188	17 86	16 67	60 49	57.97
Greece	4	6	0 10	0 12	0 10	0 12
Ireland	51	49	1 67	2 02	1 67	2 02
Italy	289	290	16 32	16 63	40 05	41 57
Luxembourg	-	-	-	-	0 48	0 50
Netherlands	1,770	1,730	75 28	66 00	43 73	39 26
Norway	2,285	2,298	29 42	29 83	1 35	1 57
Spain	24	23	0 72	0 92	3 21	4 17
Sweden	-	-	-	-	0 32	0 33
Switzerland	-	-	-		1 54	1 45
United Kingdom	644	590	47 64	45 75	59 90	57 10
Yugoslavia	88	90	2 89	3 02	7 32	7 82
EASTERN EUROPE	42,396	43,136	790 46	828 82	747 77	784 39
Albania	9	10	0 75	0 80	0 75	0 80
Bulgaria	5	5	0 13	0 15	6 20	6 55
Czechoslovakia	15	14	0 74	0 87	11 38	11 97
German DR	187	175	13 08	12 00	19 96	19 10
Hungary	119	112	7 11	6 30	11 88	11 30
Poland	163	158	5 75	5 70	13 28	13 60
Romania	198	162	35 50	33 00	38 76	36 50
USSR	417,000	42,500	727 70	770 00	645 56	684 57

Table IIa (cont.)

Unit 10⁹ m³	Proved reserves at year s end		Marketed production		Consumption	
	1987	1988	1987	1988	1987	1988
NORTH AMERICA	7 994	7 784	553 20	570 71	551 88	569 91
Canada	2 693	2 637	84 96	98 22	57 04	62 69
USA	5 301	5 150	468 24	472 49	494 84	507 22
LATIN AMERICA	7 090	7 260	76 15	81 17	76 21	81 24
Argentina	693	771	15 15	18 96	17 42	21 19
Colombia	112	114	4 06	4 14	4 06	4 14
Mexico	2 119	2 074	26 36	26 14	26 42	26 21
Venezuela	2 842	3 000	18 66	19 68	18 66	19 68
ASIA	38 969	42 528	192 92	210 21	192 98	210 21
Bahrain	198	263	5 07	5 50	5 07	5 50
China	900	1 000	13 44	13 75	13 44	13 75
India	1 005	1 050	7 53	8 66	7 53	8 66
Indonesia	2 367	2 464	35 91	38 02	13 79	13 44
Iran	14 000	14 200	16 00	20 00	16 00	20 00
Japan	40	38	2 23	2 10	41 54	44 00
Kuwait	1 205	1 378	4 78	6 49	7 53	9 59
Malaysia	1 487	1 472	15 58	16 45	7 57	8 19
Pakistan	626	651	11 88	12 59	11 88	12 59
Qatar	4 440	4 621	5 61	6 47	5 61	6 47
Saudi Arabia	4 136	5 020	26 80	29 10	26 80	29 10
Thailand	184	212	4 44	5 46	4 44	5 46
UAE	5 197	5 180	12 61	12 92	9 74	9 74

Table IIb World natural gas proven reserves, marketed production and consumption, continued

Unit 10⁹ m³	Proven reserves year s end		Marketed production		Consumption	
	1987	1988	1987	1988	1987	1988
AFRICA	7 337	7 700	59 15	62 13	33 49	35 71
Algeria	2 999	3 230	43 17	44 90	17 42	18 64
Egypt	307	332	6 28	6 92	6 28	6 92
Libyan AR	727	722	5 00	5 50	4 20	4 44
Nigeria	2 407	2 476	3 70	3 80	3 70	3 80
OCEANIA	2 308	2 445	17 85	18 65	17 85	18 65
Australia	2 238	2 300	13 87	14 08	13 87	14 08
WORLD	111 678	116 283	1 889 06	1 959 47	1 889 06	1 959 47

Table IIc World natural gas proven reserves, marketed production and consumption (percentage share of world total), continued

Unit 10⁹ m³	Proved reserves at year s end		Marketed production		Consumption	
	1987	1988	1987	1988	1987	1988
WESTERN EUROPE	4 9	4 7	10 6	9 6	14 2	13 2
EASTERN EUROPE	38 0	37 1	41 8	42 3	39 6	40 0
NORTH AMERICA	7 2	6 7	29 3	29 1	29 2	29 1
ECE REGION	50 1	48 5	81 7	81 0	83 0	82 3
LATIN AMERICA	6 3	6 2	4 0	4 1	4 0	4 2
ASIA	34 9	36 6	10 2	10 7	10 2	10 7
AFRICA	6 6	6 6	3 1	3 2	1 8	1 8
OCEANIA	2 1	2 1	1 0	1 0	1 0	1 0
WORLD	100 0	100 0	100 0	100 0	100 0	100 0

Table III Proven gas reserves and exportable surpluses, as of December 31, 1987

Unit: Tcf	Proven reserves	Exportable surplus
USSR	1,450	809
Iran	489	158
United States	87	0
Abu Dhabi	184	155
Qatar	157	152
Saudi Arabia	140	0
Algeria	106	40
Canada	95	12
Venezuela	95	14
Norway	89	56
Nigeria	84	67
Australia	79	53
Mexico	76	0
Indonesia	73	46
Netherlands	64	10
Malaysia	52	29
		0
Other Middle East	122	
Other Asia Pacific	113	25
Other Europe	77	3
Other Latin America	61	31
Other Africa	6	6
Total World	3,849	1,666

2.2. Undiscovered Resources

2.2.1. Conventional Gas

Besides proven reserves, a large resource base of "conventional", undiscovered gas resources exists world-wide. These resources are generally defined as natural gas not yet discovered, but which general geological and engineering judgement suggests may eventually be recovered economically. Estimates of these resources pose greater uncertainty than in the case of proven reserves but their presence has often been proven over time by drilling. For many estimators, there is a fine line of separation between "proven" and "undiscovered" resources, giving rise to such terms as "probable", "speculative", "possible" reserves or resources. Because of the greater uncertainty associated with undiscovered resources, most estimators assign a range of probabilities as to their likely occurrence. In the case of the WPC report, the undiscovered resource for natural gas, as of 1 January 1985, was in the range of 75.1×10^{12} m^3 and 243.3×10^{12} m^3, with the probability range of occurence of 95% and 5%, respectively. The mode was 119×10^{12} m^3 (Table I). The regional distribution of these undiscovered resources, as in the case of proven reserves, is concentrated in the Middle East, with 22.3% of the mode; the USSR with 29.2%; and North America, with 16.6%, where Canada accounts for more than half and the rest is in Mexico.

2.2.2. Unconventional Gas

Besides potential sources of "conventional" gas (gas usually found in porous and permeable reservoir rocks or "traps") there are several other sources of methane generally classified as "unconventional" gas [6], some of which are being produced commercially in some countries but which on the whole require improved or new technology and/or improved economics to produce commercially on a large scale.

2.2.2.1. Tight Gas Formations

Geologically, tight formations are similar to those with accumulation of "conventional" gas. "Tight" refers to the low porosity and very low permeability of the formations to produce the gas. Wells drilled in these types of formations are very low gas producers. They often require special fracturing techniques to stimulate production.

Although the resource potential for tight gas worldwide is not well known or established, large deposits do exist in the United States and in the Deep Basin of Alberta, Canada. There is also also reason to believe that similar deposits exist in other sedimentary basins of the world.

In the USA, through economic incentives, such as higher well-head prices and special tax, commercial production exists from wells drilled in these formations. Research funded by the government to promote the production of "unconventional" gas has also contributed to a better understanding of this resource, including production techniques. In the USA, such "tight" formations have been estimated to contain in the range of 433 trillion cubic feet (tcf) to 945 tcf, of which some 56 tcf to 105 tcf could economically be recovered with a wellhead price of US$3 per thousand cubic feet (mcf).

2.2.2.2. Shale Gas

"Shale" gas deposits generally refer to Devonian shales, rich in organic matter and occuring throughout much of the Eastern United States. Similar deposits are likely to exist elsewhere in the world. Thick organic rich shale deposits are not uncommon. Estimates of this resource in the U.S. range from 387 tcf to 3,900 tcf. The amount that technically could be recovered is relatively modest, about 31 tcf, of which 10 tcf could be recovered with a wellhead price of about US$3 per mcf.

2.2.2.3. Coal-bed Methane

The resource potential for coal-bed methane is very large, given the extensive worldwide occurence of coal deposits. In the USA, the resource base has been estimated to range from 72 tcf to 860 tcf. This wide range reflects in part the uncertainties associated with the parameters of occurence, its abundance, and economics of recovery. This source of methane is nonetheless being produced commercially in the USA in certain regions with coal deposits known to contain a high presence of methane. The commercial development of this resource requires close collaboration with the coal industry. In many countries, methane associated with coal production is considered a safety problem. Furthermore, given the low rate of a production from wells drilled in coal seams, and often the isolation of these sources from gas markets, commercial production is expected to be limited.

2.2.2.4. Hydrates

The resource potential for methane from hydrates is quite speculative and less is known about their degree of occurrence. Gas hydrates generally form in high-pressure low-temperature environments, such as permafrost or within sea-bed sediments. Estimates of the volume of methane in hydrates in the Alaskan permafrost range from 11 tcf to 25,000 tcf. In the Soviet Union, where there has been some production, the resource potential is as much as $1{,}000 \times 10^{12}$ m^3. Similar deposits are known to exist in the offshore of the USA and the North Sea.

2.2.2.5. Geopressured Aquifers

This resource consists of natural gas, mostly methane, that occurs dissolved in geopressured-geothermal reservoirs. The nature of these deposits is based on the fact that methane can dissolve in water, more so at greater depths, and geologists believe that most sedimentary basins will have large parts of their formation water saturated with gas.

Tests have been carried out in the USA to produce this source of methane. To produce it commercially gives rise to disproportionate amounts of salt water, creating disposal problems. The resource potential is enormous. In the USA coastal regions of the Gulf of Mexico, it has been estimated to be in the order of 160 tcf.

All of these "unconventional" resources, with the exception of tight formations, Devonian shales and coal-bed methane, are quite speculative. They require better knowledge of their characteristics and production behavior, new technology, and significantly better economics to produce them commercially. In a gas supply environment where "conventional" gas is readily available at lower cost, the need to develop these resources is influenced by the conditions of the gas market and rate of depletion of conventional gas sources. This has been demonstrated in the USA, where intensive drilling for conventional gas and its high rate of depletion, has provided the framework for government and industry to co-operate and support their commercial development.

It is important to recognize that in judging and evaluating the resource base for gas and its future prospects against the availability of other energy sources, such as coal and oil, both conventional and unconventional gas be taken into account in shaping the long-term perspective of this energy source.

3. NATURAL GAS PRODUCTION

World marketed production[1] of natural gas has experienced constant, steady rates of growth, averaging 3.3% annually during the past decade and slightly more between 1983-1988 [5] (Table IV). Production, which in the 1950s was concentrated in North America, began to increase in the 1960s in Western Europe and the Soviet Union.

[1] Marketed production is gross production less volumes of gas re-injected, flared or other losses.

Table IV Evolution of world natural gas production

Unit: 10^9 m^3	Gross production	Re-injection	Flaring	Other losses	Marketed production	Rate of utilization %
	(1)	(2)	(3)	(4)	(5)	(6)
1960	613.6	72.2	75.9	20.3	445.2	75.9
1970	1331.1	84.9	160.8	44.5	1040.9	81.5
1975	1571.3	77.9	173.2	52.2	1268.0	84.0
1980	1860.1	112.9	164.1	58.5	1524.6	85.1
1981	1877.6	132.7	126.1	68.3	1550.5	86.2
1982	1876.6	148.7	111.1	66.7	1550.1	86.2
1983	1890.4	155.6	98.8	79.4	1556.6	86.5
1984	2037.7	166.4	99.8	84.9	1686.6	86.9
1985	2111.9	171.0	104.4	88.3	1748.2	87.0
1986	2167.4	176.1	100.0	94.2	1797.1	87.3
1987	2282.1	199.5	92.3	101.2	1889.1	87.2
1988	2368.2	209.1	92.4	107.2	1959.5	87.3

(4): Shrinkage resulting from natural gas processing for purification and extraction of liquefiable fractions (NGL)
(5) = (1) - (2) - (3) - (4)
(6) = (Utilized production/Gross production) = [(1)-(2)-(3)]/(1)

Between 1960 and 1988, production increased from 445x10^9 m^3 to 1,959x10^9 m^3. During this period of growth, measures were taken by oil and gas producers to prevent the waste of this valuable resource through venting or flaring gas.

In 1960, for example, 12.4% of the world's gross production was flared compared to 3.7% in 1988. Much of this reduction occurred in the Middle East, where gas gathering facilities were built to recover and process associated/dissolved gas for LPG and methanol production.

The R/P ratio in 1988 was 54 for the world but 270 in the case of the Middle East; 81 in the case of Africa; 72 in Asia/Oceania; 67 in Latin America; 50 for Eastern Europe; 27.5 for Western Europe and 12.5 for North America.

These trends in world production, when viewed by regions, reflect the rate or state of development and use of gas in countries of these regions.

3.1. North America

North American production during the 1970s and early 1980s experienced a decline, primarily in the USA, where it declined by 13% between 1978 and 1988. It made a modest recovery in 1987 and 1988, amounting to 472x10^9 m^3 in 1988. The decline was due primarily to reduced demand, competition from alternative fuels (primarily fuel oil), and greater access to competitively priced Canadian gas exports. Canada also experienced a decline in the mid- 1980s, but in 1988 it recovered when production increased by 4%, to 96x10^9 m^3.

3.2. Western Europe

In Western Europe, production increased significantly in the 1970s, while during the 1980s it experienced moderate increases, with some decline, due primarily to reduced demand and market competition from alternative fuels. In 1988, production declined by 6% to 188x10^9 m^3. The leading producers in Western Europe are the Netherlands, with a 1988 production of 66x10^9 m^3, the United Kingdom, with 46x10^4 m^3, and Norway, with 30x 10^9 m^3. These three countries accounted for 75.4% of the total production. Production from the United Kingdom is used exclusively for the domestic market, whereas the Netherlands and Norway are important sources of supply to a number of countries in continental Europe. There is no domestic market for gas in Norway and all of its production is exported. A few other countries in Europe, such as Italy, France and the Federal Republic of Germany, have some domestic production but gas imports have become an integral and growing part of their gas supply needs. Denmark has also become a producer and exporter of gas. On the whole, most Western European gas markets, some of which have little or no domestic production, rely on imports.

3.3. Eastern Europe

In Eastern Europe, the major producer is the Soviet Union, which in 1983 became the world's leading producer, surpassing the United States. The Soviet Union has achieved remarkable success in increasing its production, doubling in a decade, amounting to 770x10^9 m^3 in 1988. Most of this production is centered in Western Siberia, which provides about half of the country's total output. With some of the world's largest deposits of gas, the Soviet Union could significantly increase its production, but may be limited by other factors that have recently developed in setting an agenda for its future economic development. Other countries in Eastern Europe, with the exception of Romania, have limited indigenous production, and rely primarily on imports from the Soviet Union to satisfy domestic requirements. A number of these countries still rely for about 15% to 30% of their gas supply on manufactured gases, which are slowly being replaced with natural gas.

3.4. Middle East

Gas production in the Middle East has experienced some decline in recent years, due primarily to the loss of production in Iran, which has been slowing restoring its production facilities. Most of the gas produced in this region is associated/dissolved gas. The major producers are Iran, Saudi Arabia and Abu Dhabi, which accounted for 65% of the 95x10^9 m^3 produced in the region in 1988. Iran alone has proven reserves second only to those of the Soviet Union. It may in time become another source of gas supply to Europe.

3.5. Asia/Oceania

This region is a latecomer in the development of large gas resources available in a number of countries of the region. Production in the region increased by 28% in the span of a little over a decade, to 134x10^9 m^3 in 1988. Major producers are Indonesia (38x10^9 m^3); Malaysia (16.5x10^9 m^3) and Pakistan (12.6x19^9 m^3). China has also emerged as a producer of gas, with 1988 production of 14x10^9 m^3. Much of this production is exported in the form of LNG in Japan, Republic of Korea and Taiwan (China). Australia has also recently been aggressively developing its gas resources and has become an exporter of gas. This region is perhaps the most dynamic area in terms of developing its substantial gas resources and expanding the use of gas throughout the region. Both for environmental reasons and energy, needs for the booming economies of a number of countries in the region, natural gas is in a favourable situation for further growth.

3.6. South America

Production in Latin America in 1988 amounted to 81x10^9 m^3, with only few countries in the region having natural gas production, such as Mexico, Argentina and Venezuela. The lack of a developed gas pipeline and distribution infrastructure has slowed the development of gas markets. It is also a region where production, as in the case of Venezuela and Mexico, is influenced by the oil market. Mexico, which in the past had exported some gas to the USA, ceased being an exporter as part of its economic strategy to use gas for its economic development. Because of its close proximity to the USA market, it may in time resume exports. Venezuela, which like Mexico, has large associated/dissolved gas production, is considering plans to structure an LNG export project for the USA gas market.

3.7. Africa

Few countries in this region have developed their gas resources to achieve production or to develop meaningful gas markets. Nonetheless, it is a region where Algeria has some of the world's largest deposits of gas, with production in 1988 of about 45x10^9 m^3 and proven reserves of about 3,200x10^9 m^3. Algeria was one of the leading promoters of LNG trade, making it an important source of gas supply to Western Europe. The exploitation of its hydrocarbon resources became a cornerstone of the country's economic development, which remains so as the country seeks new gas market outlets in Europe and elsewhere. Other producers in the region which have developed their gas resources are Libya, making it one of the early exporters of LNG. Egypt has implemented a strategy to use gas for its domestic markets. Nigeria with substantial associated/dissolved gas production, much of which is flared, is in the process of trying once again to develop an export market.

4. OFFSHORE PRODUCTION

One of the great success stories of the world petroleum industry is the extent to which it has developed the technology to explore for and develop hydrocarbon resources in the offshore area, extending in water depths in excess of 1,000 meters and in some very hostile environments, such as the North Sea. The offshore has become an essential source of hydrocarbons in a relatively short time, not only of crude oil but also of natural gas as well. In 1988, some 361x10^9 m^3 (18.4% of the world's marketed gas production) was produced in the offshore. In 1970 it was only 11.6%. For the USA, the first country to develop its offshore resources in the Gulf of Mexico, offshore production has become an important source of gas supply, as is also the case in the North Sea, and recently, the Pacific Basin region. In the USA, offshore production in 1988 accounted for 29% of the country's total production of gas. In Western Europe, the offshore amounted to 110x10^9 m^3, accounting for 58.6% of the region's total production. Norway and the United Kingdom are the major producers. The Netherlands and Denmark have also made important gas discoveries in their offshore areas. Italy and Yugoslavia have achieved success in finding some gas deposits in the Adriatic. In the Asia/Oceania region, Malaysia is the leading offshore producer, with Brunei having some production. Other countries in the region are planning to explore for and develop their offshore production potential, as in the case of India and Indonesia, as well as Australia, with the development of its North-West Shelf project for LNG exports.

Development of offshore gas resources is an expensive undertaking. It requires special technology, a high degree of integrated safety and environmental control measures to drill for and develop these resources. The petroleum industry constantly strives to reduce these costs through improved technology and operating practices.

5. CONSUMPTION

The apparent world consumption[2] of natural gas in 1988 was 1959×10^9 m^3, an increase of 3.7% over 1987 (Table II). By regions, consumption centers in Eastern Europe, with 40%, primarily in the Soviet Union; North America, with 29%; and Western Europe, with 13%. In all regions, consumption has increased over the years, with the exception of North America, where it declined in the USA in the late 1970s and early 1980s. Consumption has recovered since then and is expected to continue on an upward trend.

Natural gas is essentially a fuel, and is used extensively in the domestic/commercial sector and in industry. The extent to which it is consumed in these sectors varies among regions and individual countries. It is dominant in most developed gas markets of North America and Western Europe.

The penetration of natural gas in energy sectors is influenced by a number of factors, such as the availability of gas supply, e.g., indigenous production and/or imports, the state and rate of development of a gas industry infrastructure, availability and market behaviour of alternative energy sources, prevailing government policies, energy/economic development, etc. Environmental factors have already influenced a number of governments to promote natural gas. For developed, mature gas markets, which have an extensive gas distribution system in place, growth in demand can be more easily accommodated, but increased competition from alternative fuels has an impact on rates of growth in consumption. In developing markets, as is the case for a number of countries in the Mediterranean region and in the Nordic countries of Europe and much more so in the rest of the world, natural gas consumption will experience more gradual, moderate rates of growth because of the time and investments required to build the industry infrastructure. An important factor which may well shape the rate of growth of gas in industrialized countries is "opening" the market for electric power generation, which in the past was restricted in some countries due to the perceived notion that its resource potential was limited and gas supplies were scarce. However, new and improved technologies in electric power generation, through higher efficiencies achieved by combined-cycle generation and co-generation, have given natural gas an added market potential in this sector. Another possibility exists in the transportation sector where natural gas is used selectively in some countries as a vehicle fuel as compressed natural gas (CNG), especially for captive vehicle fleets. The potential for a more widespread use of gas for this purpose hinges on a significant increase in oil prices to make investments in the infrastructure to support such use and consumers' acceptance.

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[2]Consisting of marketed production plus net imports, but excluding stock exchanges/storage.

6. GAS TRADE

6.1. Gas Pipeline Trade

Gas pipelines are the most convenient and efficient means for delivering natural gas to markets. The technology for delivering gas over long distances through high pressure large-diameter pipelines, is well developed, for both onshore and offshore. Gas markets, which initially developed by relying on locally produced natural gas, extended their gas pipeline systems to connect external sources of supply in close proximity to their markets, e.g. USA and Canada.

In North America, USA and Canadian gas pipeline companies began to develop an integrated gas pipeline system in the 1950s to import Canadian gas available in the Western Provinces of Canada, which at the time had a limited internal gas market. This changed, however, with the completion of the Trans-Canada Pipeline, extending east-west some 1,200 miles to serve Canadian consumers in the Eastern provinces. This pipeline provided an important link for exporting Canadian gas to USA gas markets across the border.

In Western Europe, gas pipelines expanded their system to receive gas from the Netherlands, followed by imports from the Soviet Union and later the North Sea. Some of these pipelines were linked to terminals to receive LNG imports. Large gas pipeline enterprises, such as RuhrGas, SNAM, Gasunie, Gaz de France and others, in order to acquire long-term large supplies of gas, formed consortia and joint ventures to construct and operate gas transmission systems for routing gas across national boundaries. In Eastern Europe, the Soviet Union and a number of other countries in the region collaborated in the development of their respective gas markets and gas pipeline infrastructure that benefited the Soviet Union in developing its vast gas resources for the domestic and export market. This form of co-operation contributed significantly to the development of an integrated gas system in Western Europe. It is a system undergoing further growth as the relatively new and emerging gas markets in the periphery of Western Europe, such as Spain, Sweden, Denmark, Finland, Ireland, Turkey and possibly Greece and Portugal, proceed with plans to expand their gas grids or make plans to introduce natural gas.

In some gas markets, the traditional role played by gas pipelines has undergone marked changes in recent years. In North America, Government policies in both the USA and Canada have, through de-regulation affecting every segment of the gas market, created a more market oriented, competitive gas industry. In the past, pipeline companies performed the function of acquiring gas supplies from producers, which they sold to consumers. Through regulatory changes, this function has changed to the point that now pipelines transport gas that customers acquire directly from producers, instead of relying on the pipelines to do so, and pay a fee to the pipeline carrier. In 1987, for example, transportation service of USA inter-state gas pipelines accounted for 67% of the volume delivered by these pipelines. Similar arrangements exist in the Canadian gas industry.

In Western Europe, the Commission for the European Community, as part of its programme to create an internal energy market among its member countries, has proposed rules along the same lines as those in effect in the USA, to permit end-users or consumers of gas to acquire gas directly from producers and require pipelines to transport the gas. This proposal is opposed by the major carriers of gas, whereas some gas distribution enterprises and large consumers such as the petrochemical industry, favour "opening" the market. Pipelines argue that this change jeopardizes the viability to acquire long-term supplies from exporters and security of supply would be at risk. They also foresee reduced investments for new pipelines. Consumers in favour of this change argue that "opening" the market will create a more competitive, efficient gas industry, that should benefit all consumers.

In Central and Eastern Europe, marked political and economic changes are creating new challenges for gas enterprises, as many of these countries, such as Hungary, Poland and Czechoslovakia, have declared their intentions to acquire gas supplies outside the Soviet Union, which may lead to a more fully integrated all-European gas system.

One factor that tends to limit pipeline trade is its inflexibility. It requires that a market for the gas be secured well in advance, involving extensive and complex negotiations prior to initiating construction, with terms of sale extending for 20 years or more to allow recovery of the investments.

In 1988, gas pipeline trade amounted to $205x10^9$ m^3, an increase of 4.3% over 1987 [5]. This volume of trade accounted for 10.4% of the world's marketed natural gas production. In 1970, this form of trade amounted to only $43x10^9$ m^3, or 4.1% of the marketed production (Figs. 9 and 10, Table V). Pipeline gas exports are highly concentrated in a few countries. In 1988, for example, five countries accounted for 94% of the exports: the Soviet Union, with $87.8x10^9$ m^3 (40.8%); the Netherlands, with $28.9x10^9$ m^3 (14.1%); Norway, with $28.3x10^9$ m^3 (13.8%); Canada, with $35.9x10^9$ m^3 (17.5%); and Algeria, with $11.4x10^9$ m^3 (5.6%). Imports, on the other hand, are more diffused, principally in countries of Europe and North America. Some limited pipeline trade also exists in the Middle East, South America and the Pacific Basin.

Relative to prices, the presence of a "buyer's" market has favoured buyers in recent years, as contractual terms both in terms of prices and volume-offtake have been re-negotiated, causing a decline in the export market price for gas. In the USA, prices on a CIF basis have declined from a range of US$4 to US$5 per million Btu (MBtu) in 1984 to about US$2 per MBtu in 1988. In Western Europe, prices declined from a range of US$3.5 to US$4 per MBtu to US$ 1.7 to US$2.30 per MBtu during the same period, and in Japan, which consistently pays a relatively higher price for gas imports, prices declined from a range of US$4.8 - US$5.2 to about US$2.70 - US$3.0 per MBtu. These are prices quoted in the trade press, since terms of sales in gas trade agreements are surrounded with commercial secrecy.

The tendency in recent years is to negotiate for prices that reflect the competitive market conditions of energy of consuming markets. This concept, referred to as "net back" pricing, starts with the price at the end-use level and works back to arrive at the selling price by the producer. This recent trend is likely to continue in the future, provided energy prices, especially oil prices, remain stable. A factor which may influence gas prices is a shift from a "buyer's" to a "seller's" market, a prospect that some analysts foresee developing in the mid-1990s, as demand for gas increases and negotiations take place to acquire new sources of gas supply.

Table V Estimate of international gas trade by pipeline in 1988 (10^9 m^3)

Export / Import	NORTH AMERICA			LATIN AMERICA	WESTERN EUROPE					EASTERN EUROPE	AFRICA	MIDDLE EAST			ASIA OCEANIA	TOTAL IMPORTS BY PIPELINE
	Canada	USA	Total	Bolivia	Den-mark	Nether-lands	Norway	Germany FR	Total	USSR	Algeria	Iraq	Shar-jah	Total	Afghanistan	
NORTH AMERICA	35 91	0 38	36.29													36 29
Canada		0 38	0 38													0 38
USA	35 91		35 91													35 91
LATIN AMERICA		0 07	0 07	2 23												2 30
Argentina				2.23												2 23
Mexico		0 07	0 07													0 07
WESTERN EUROPE					0 83	28 87	28 26	1 10	59 06	45 73	10 53					115 32
Austria								0 10	0 10	3 78						3 88
Belgium						3 91	1 85		5 76							5 76
Finland										1 62						1 62
France						3 03	5 23		8.26	8 14						16 40
Italy						4 35			4 35	9 87	10 53					24 75
Luxembourg						0 50			0 50							0 50
Netherlands							2 13		2 13							2 13
Spain																
Sweden					0 33				0 33							0 33
Switzerland						0 40		1 00	1 40	0 05						1 45
United Kingdom							11 30		11 30							11 30
West Germany					0 50	16 68	7 75		24 93	17 47						42 40
Yugoslavia										4 80						4 80
EASTERN EUROPE										41 00					2 40	43 40
Bulgaria										6 40						6 40
Czechoslovakia										11 10						11 10
East Germany										7 10						7 10
Hungary										5 00						5 00
Poland										7 90						7 90
Rumania										3 50						3 50
USSR															2 40	2 40
AFRICA											0 90					0 90
Tunisia											0 90					0 90
MIDDLE EAST										1 10		3 10	2 18	5 28		6 38
Dubai													1 50	1 50		1 50
Kuwait												3 10		3 10		3 10
North Emirate													0 68	0 68		0 68
Turkey										1 10						1 10
ASIA/OCEANIA																
Japan																
South Korea																
TOTAL EXPORTS BY PIPE	35 91	0 45	36 36	2 23	0 83	28 87	28 26	1 10	59 06	87 83	11 43	3 10	2 18	5 28	2 40	204 59

6.2. Liquified Natural Gas (LNG) Trade

Liquified natural gas (LNG) is essentially methane which is liquified by lowering the temperature to minus 161°C (-161°C). Its virtue lies in its high density in liquid form, occupying 1/600 of the space it requires as a gas at room temperature and atmospheric pressure. The gas industry has made use of this property for years for gas storage purposes. With rising demand, higher energy prices, more efficient liquification processes, improved material, and the development of special sea-going vessels to deliver the LNG, it became an alternative to pipelines to connect distant sources of gas supply to markets. The first commercial base load LNG project began in 1964, with Algeria delivering LNG to the United Kingdom.

Because of its extreme low temperatures, LNG requires special materials and processing equipment. It poses serious safety hazards. Rigid codes and standards have been developed in the design, construction, maintenance and operation of LNG systems. A typical layout of an LNG export/import project is shown in Fig. 11. Because of safety and environmental considerations in selecting sites for a project, the gas industry can and has experienced strong public reaction to the location of LNG sites. The problem is less evident in producing countries, but in consuming countries such as the USA and Western Europe, serious public opposition has delayed or at times caused a rejection of sites for import terminals.

The period of rapid growth of LNG trade occurred in the late 1960s and early 1970s, when several sources of gas supply in producing countries of North Africa and the Middle East began serving the USA, Western Europe and Japanese markets. As LNG trade developed, economy of scale led to increased sizes of liquifaction facilities. Tankers increased from 25,000 m^3 and 75,000 m^3 to 125,000 m^3. In anticipation that LNG trade would continue to increase into the 1980s, some LNG ships were built on speculation. With a decline in the number of projects, some LNG ships became idle and some were sold as scrap.

LNG projects are capital intensive, since they require substantial initial investments. They require for both the exporter and the importer long-term commitments in gas supply. Contract terms can extend for 20 years or more. Capital costs for a project can vary significantly, depending on financing, size of the project, cost terms, foreign exchange rates, subsidies, etc. A typical project, involving a volume of trade of about 15×10^9 m^3 per day, could cost in the order of US$2.5 to US$4.5 billions, of which about US$1.1 to US$2.8 billions would cover liquification facilities; US$400 to US$600 millions for a receiving terminal; and US$200 to US$220 million per ship (five ships of 125,000 m^3 capacity) would be needed. These investments exclude related pipeline facilities to connect the terminals to production and market sites. The financial exposure of both the producer and importer is sizeable, placing LNG projects at high risk. Extensive planning and negotiations are often required to initiate a project. It can take several years for a project to become operational.

There is renewed optimism in the gas industry today about the future prospects of LNG trade. Beside the prospects of additional demand for gas in the 1990s, conditions favoring sponsors of an LNG project are the availability of idle or surplus capacity in shipping and receiving terminals. Also favouring the market is the fact that a number of these projects have been in service for some 20 years or so, and the investments have been substantially amortized. Unlike trading for crude oil, where there is an active spot market, this is not the case with LNG, although occasionally some short-term spot sales have occurred. An LNG project is specifically tailored to meet the needs of a specific producer and buyer. The producer seeks to sell a specified quantity of gas annually over several years, and the buyer needs to secure a market outlet for the gas. Another market condition which is favoring LNG trade today, as in the case of gas pipeline trade, is the greater flexibility in contracts about off-take volumes and a general decline in prices.

6.2.1. LNG Markets

Relative to the total volume of gas traded internationally, LNG trade is still relative modest in size (Table VI). In 1970, it amounted to about 2.7x10^9 m^3, accounting for 0.3% of the world marketed gas production, compared to 60.5x10^9 m^3 in 1988, accounting for 3.1% of marketed production. LNG trade developed to serve gas markets in three specific areas, the United States, Western Europe and Japan, followed later by a number of countries in the Asia/Pacific region.

Table VI Estimate of international gas trade by LNG Tanke in 1988, Unit: 10^9 m^3

Exporting / Importing	USA	Algeria	Libya	Abu Dhabi	Brunei	Indonesia	Malaysia	TOTAL BY TANKER
USA		0.57						0.57
Belgium		2.88						2.88
France		8.95						8.95
Italy			0.19					0.19
Spain		2.38	0.87					3.25
UK		0.05						0.05
Germany FR								-
Japan	1.30			3.18	7.25	21.91	8.26	41.90
South Korea						2.67		2.67
TOTAL EXPORTS	1.30	14.83	1.06	3.18	7.25	24.58	8.26	60.46

6.2.1.1. United States

In the 1970s, in the face of diminishing available gas supply, a number of major gas pipeline companies embarked on a major program to import LNG. Although a number of sources of supply were being considered, Algeria became the dominating player in this form of gas imports. Imports peaked in 1979 at about 7.5x10^9 m^3, but because of disputes between importers and Algeria on prices, and the increased availability of domestic production due to the higher wellhead prices implemented through the Natural Gas Policy Act of 1978, LNG imports declined, virtually ceasing in early 1980. Imports from Algeria, in small volumes, resumed in 1988. LNG imports for the USA gas market face competition from Canadian gas exports, which have increased substantially in recent years. Nonetheless, there are four LNG terminals in the USA, with their total capacity being underutilized. This condition favours the economics for a resumption of such trade.

The USA gas market is poised for growth in the 1990s, especially with the opening of the market for electric power generation and environmental pressures to substitute gas for oil and coal in other market sectors. With the prospect of a continued decline in domestic production, gas imports will rise. In response to these market prospects, some new LNG projects are being considered, such as importing LNG from Nigeria, Norway and possibly Venezuela. With exception of the Nigerian project, the other projects are quite speculative at this stage.

6.2.1.2. Western Europe

Several countries in Western Europe have served as important outlets for LNG. These imports have become an integral part of the gas supply available to these countries. There are 9 LNG terminals operating in Western Europe. One in Italy, one in the United Kingdom, three in France, one in Belgium, and three in Spain. The principal supplier is Algeria, with Lybia exporting small quantities as well. LNG imports in 1988 amount to $15.3x10^9$ m^3 accounting for only 6% of Western Europe's total consumption, but representing an important source of gas supply for some importing countries. LNG exports to Western Europe, as in the case of pipeline exports, compete against national markets where the consumption of gas varies considerably by sectors, and are influenced by competition from alternative fuels and prevaling policies of governments on energy and specifically on energy imports.

Furthermore, established gas markets in Europe, as in the case of countries noted earlier, have developed a well diversified portfolio of gas supplies, and LNG is one of the options available to them to increase gas imports. Algeria is very active in retaining and expanding its gas markets share in Europe, where LNG imports will increase in the future, as recent new LNG projects have or will become operational in Spain, Turkey and possibly Greece and Portugal. Some central and eastern European countries are also exploring the possibility of importing Algerian gas. Algeria has substantial proven gas reserves to support growth in gas requirements in western Europe.

Besides Algeria, Nigeria is the most likely new source of LNG exports to enter the European market in the mid to late 1990s.

6.2.1.3. Nigerian Project

For several years, Nigeria has been evaluating a project to utilize its extensive production of associated/dissolved natural gas, much of which is flared. Proven and probable gas resources in Nigeria are about $2,400x10^9$ m^3, split 50/50 between associated and non-associated gas. An LNG project is taking shape, with parties involved in the project agreeing to take about $130x10^9$ m^3 of gas over a period of 20 years. Plans are to make use of existing available surplus tankers, which could be leased or acquired at significant lower cost than for new ships. The estimated cost of the project, covering gas transmission pipelines, liquefaction plant and six ships, is about US$2 billion in 1988 dollars.

Negotiation have been in progress with four gas enterprises in Western Europe, involving three LNG terminals, with the likely destination of the gas being the Federal Republic of Germany, Italy and Spain. Similar discussions are in progress with some gas companies in the United States. Pricing terms for the sale have not been revealed, although Nigeria officially states that the pricing basis will reflect competitive fuels in the main markets, taking into account the particular characteristics of LNG. The contract will also contain high take-or-pay or equivalent obligations to render the project economical. An optimistic date for initial deliveries is the mid 1990s.

6.2.1.4. Asia and Pacific

The dominant market for LNG trade is the Asia/Pacific Region, where for geographical and technical reasons, pipeline trade is less feasible. Japan has been the dominant buyer, importing in 1988 $41.9 x 10^4$ m^3 (69.3% of the total LNG trade). Its sources of LNG are quite diversified, including from Indonesia, Malaysia, Brunei, Abu Dhabi, Australia and Alaska.

Japan, one of the first countries to import LNG for electric power generation as a measure to reduce air pollution, is poised for increased imports in the 1990s, perhaps reaching 50 to $55 x 10^9$ m^3 in 2000.

The Asian market, which in the past was confined to Japan, has grown in recent years, with Taiwan (China) and the Republic of Korea entering the LNG market. The principal source of exports in the region is Indonesia, the world's largest exporter of LNG, followed by Malaysia and Brunei. These three countries accounted for 75% of the export volume, with the remainder coming from Abu Dhabi, Australia and Alaska.

In mid 1989, the placement into service of the North West Shelf Project by Australia, exporting LNG to Japan, is likely to make Australia another important source of gas in the region. Unlike the USA and European gas markets, where gas serves the needs of various end-use sectors, much of the LNG imported in this region is for electric power generation. Most governments of these countries have endorsed natural gas to deal with environmental problems, and energy needs have increased significantly due to high rates of economic growth and the desire to diversify energy supplies.

6.3. LNG Pricing

LNG prices in large measure reflect the behaviour of world energy prices and oil in particular. As noted earlier, LNG projects are tailored for specific markets and thus no international pricing standards exist, as in the case of oil. In the 1970s contract prices generally contained adjustments linked to inflation and currency fluctuations, followed by contract clauses which adjusted prices (on a fob basis) to alternate fuels. Beginning in the 1980s, contract prices started to change and were linked to crude oil prices (on a cif basis) e.g. price parity at the point of delivery. With the collapse in oil prices in 1986, LNG prices declined in the range of US$2 to US$3.50 per Million Btu, with a higher price range for the Japanese market and lower range for the USA and Western Europe markets.

7. GAS STORAGE

Natural gas storage serves an important and often essential function in the operation and management of gas enterprises. It provides the gas industry with perhaps the most efficient means of balancing supply and demand, especially in gas markets with seasonal fluctuations in demand, where large numbers of domestic and commerical consumers exist. Gas storage is integrated in the planning and operation of gas pipeline/distribution systems to supplemental supplies of gas during peak demand periods. Storage also allows gas enterprises to operate gas pipelines at higher load-factor, thus reducing the ultimate cost of gas service to customers.

In combination with other measures, such as serving customers with interruptable service, e.g., consumers which normally have dual-fuel burning capability, storage enhances reliability and security of gas supply in the event of curtailment or interruption of gas supplies.

The need for storage does not normally occur until such time as a market begins to develop an infrastructure to serve consumers which experience seasonable variations in demand. It is not uncommon for countries which have taken decisions to introduce gas into their energy markets to initially limit such sales to large, base-load consumers, such as industry and electric power generation. This type of gas development is taking place in some European countries, such as Turkey, Spain, Sweden, Denmark, and elsewhere such as Australia, where natural gas is experiencing growth in demand and the gas industry infrastructure is expanding.

The most common and preferred type of underground storage is the use of depleted oil and gas fields and aquifers. These are commonly found in countries with a history of natural gas production, as is the case in North America and in some countries of Europe. Where such sites are not available or suitable for such purpose, the gas industry uses salt and mineral cavities.

Beside underground storage, the gas industry also makes use of LNG liquefaction storage holders, normally used by gas distribution enterprises to serve consumers during peak period demand, which may extend for a few days. These types of storage are usually found in close proximity to markets served by such companies. LNG storage is also available at LNG import terminals to handle the unloading of the LNG and to provide a back-up in supplies in case of short interruptions in deliveries.

The development of an underground storage facility requires significant capital investments for wells needed to inject and withdraw gas from storage, for treating and compression facilities and for pipelines connecting the storage site to the servicing pipeline. A significant initial investment is the acquisition of the volume of gas to be injected initially into the storage reservoir, referred to in the gas industry as "base" gas, that is retained in the reservoir to provide the pressure for volume throughput during an output cycle.

The cost of this volume of base gas can be as much as 50% of the total capital investment for a new storage facility. Indicating the size of the investments for storage is the experience of the gas industry as a whole, where the total capital plant of the industry, e.g., transmission pipelines, production, distribution, etc., amounted to US$ 104 billion in 1988, of which 4.5%, or US$ 8.8 billion, was for underground gas storage.

Little underground gas storage exists in gas markets outside of North America and Eastern and Western Europe, since most of those markets have not reached the state of maturity to require storage. In North America and Europe, a well developed underground storage capacity exists and more is added to it to meet new requirements. A status of storage capacity in some regions in 1987 is shown in Table VII [7]. For most gas markets in this region, enough gas supplies are available in storage to sustain any possible interruptions of gas supplies for several weeks.

Table VII Underground gas storage, 1987

	Foot-note	Number of storage fields	Type of storage	Storage Capacity Unit: 10^6 m^3			Maximum daily output 10^6 m^3
				Cushion gas	Working gas	Total	
Austria	1	5	a	1,679	2,300	3,979	23
Belgium	2	3	b,d	375	315	690	90 #
Canada		26	a,b	7,984	4,688	12,672	81
Czechoslovakia		3	a	2,870	2,160	5,030	25.9
Denmark	3	3	c	...	...	180	...
Finland	4	...	...	...	...	...	...
France	5	13	b,c	9,600	6,700	16,300	100
Germany FR	6	21	a,b,c	6,600	4,900	11,500	128.1
Hungary		3	a	1,300	2,300	3,600	14.5
Italy		8	a	11,100	9,500	20,600	166.5
Netherlands	7	...	...	...	...	...	...
Spain	8	...	...	...	...	...	...
Sweden	9	...	...	...	...	...	...
USSR	10	...	...	...	...	...	...
UK	11	1	a	5,552	2,890	8,442	28
USA		398	a,b,c	108,000	124,000	232,00	1,040
Yugoslavia	12	1	a	450	350	0	3.5
						800	

Type of storage: a - depleted reservoirs, b - acquifers, c - salt cavities, d - mined cavities
Maximum hourly output
Footnotes

1 Further expansion of storage capacity could add an additional one third to existing storage capacity.

2 One additional aquifer storage site under construction, with a storage capacity of 500x10^6 m^3 will be "cushion" gas and the remainder "working" gas. Maximum daily output will be 8,642.4x10^6 m^3.

3 Cavities in salt deposits have been developed for storage, of which three are in operation. In 1991, storage capacity will be about 260x10^6 m^3, which will provide a back-up in supply of 10% of anticipated consumption.

4 An active testing programme underway to make use of mined rock cavaties for storage.

5 By 1990, storage capacity will increase further to 17,600x10^6.$m^3$of wich 9,700x10^6 m^3 will be "cushion" gas and 7,900x10^6 m^3 "working" gas.

6 Storage capacity is projected to increase further with working caoacity doubling by the year 2000 and working capacity likely to be in the range of 10 to 11x10^9 m^3.

7 No storage facilities in place for the present although plans exist to develop 10 storage sites in salt cavities; with a capacity in 1996 of about 500x10^6 m^3. Groningen field currently provides supply flexibility.

8 No storage facilities in place but in 1992 it is planned that about 600x10^6 m^3 will be stored in depleted fields.

9 No storage facilities in place. In joint co-operation with companies in Norway and Finland, evaluation is in progress for storing gas in deep rock caverns. Three will be developed in 1988/89.

10 Storage in various media is used, including underground storage, the extent of which is unknown. During the five year plan (1986/91) active volume in underground storage is expected to double.

11 The offshore Rough field provides production at a maximum rate of about 283x10^6 m^3 per day for up to 80 days (Capacity is 2,260x10^6 m^3). Five leached salt cavities and two more to be completed in 1989, will provide an additional capacity of 260x10^6 m^3.

12 An additional depleted reservoir for storage is under development.

8. PROSPECTS FOR THE FUTURE

The prospects for natural gas, as it is the case for energy supplies as a whole, are influenced by a number of factors, such as economic growth, trends in energy prices, tax and fiscal policies, energy policies and environmental factors, etc. Natural gas markets will develop further, as they have in the past, primarily regionally, with consuming countries favouring sources of supplies in close proximity to their markets, costs being a controlling factor. The imbalance between sources of supply and markets will nonetheless favour an expansion of gas trade. LNG trade provides an option for countries that have the financial resources and market outlets to justify the significant investments required for new grass-root LNG export/import projects. Gas pipelines may also provide an additional link to connect sources of supplies separated by large bodies of water. This was demonstrated with the Trans-Mediterranean Pipeline completed in 1982, crossing the Mediterranean, with water depths in excess of 300 meters, connecting gas supplies from Algeria through Tunisia to Sicily. More recently, the TRANSASEAN project has been launched by a number of industrial and financial companies of the European Community and Asian countries to study the possibility of constructing a 8,000 km gas pipeline system intended to develop the natural gas production and markets of Thailand, Malaysia, Singapore, Indonesia, Brunei and the Philippines. This project, estimated to cost US$ 10 billion, will require several under-sea gas pipelines.

Recent assessments of future prospects of energy supplies indicate growth in supplies and consumption. Chevron's most recent world energy outlook indicates that by the year 2000, ample sources of energy supply will be available at reasonable costs, noting that one of the important issues in the 1990s will be environmental problems arising from the use of fossil fuels. Regarding natural gas, the outlook foresees growing availability of natural gas in all regions, with the exception of the U.S. where the continual decline in domestic fuel supplies will require more imports. In the 1989 review of the energy policies and programmes of the International Energy Agency (IEA) countries, natural gas consumption for OECD member countries is expected to increase at a rate of 1.2% per annum between 1987 and 1995, and by 1.6% per annum in the year 2005.

A recent global assessment of natural gas to the year 2000 was prepared by the Association Technique de l'Industrie du Gaz en France in its report, "Natural Gas in the World, Outlook to 2000" [8]. The report notes that future gas production in the world will not be determined by the available gas resources. Distances between reserves and major consuming regions can hamper its further growth. Growth in the world production will be influenced by policies premitting gas markets to develop and the prospects for gas trade. The report concludes that to the year 2000 growth rates will be in the order of 2.5% per year, but with some regional variations. By the 2000 horizon, the report foresees a world market production of about $2{,}400 \times 10^9$ m^3, a gain of 40% over 1985. The regional distribution of this production outlook is shown in Table VIII.

In North America, the report concludes that in the U.S. there will be a continued decline in production as new gas discoveries will not be adequate to offset production. For technical and economic reasons, large gas reserves available in Prudhoe Bay in Alaska are not likely to be connected to the USA continental market soon. Canada, on the other hand, will continue to depend on the Western provinces for its production but prospects exist to connect deposits in the Arctic region and the offshore East Coast. In 2000, a decline in production in the USA but an increase for Canada is foreseen.

For Western Europe, the study predicts a decline in on-shore production for most countries in central Europe, including the Netherlands, in favour of North Sea production. By the year 2000, nearly 60% of the European production could originate in the offshore, compared with 45% in 1985. Total production in the region is expected to remain at approximately 1985 levels, i.e., at 165x10^9 m^3.

Table VIII Marketed world production of natural gas prospects to 2000

Unit: 10^9 m^3	1985	1990	1995	2000
NORTH AMERICA	513.1	522.5	501.1	490.7
- Canada	86.2	97.1	109.9	123.6
- USA	426.9	425.4	391.2	367.1
LATIN AMERICA	75.6	97.2	111.4	125.8
WESTERN EUROPE	164.8	165.7	162.8	164.4
EASTERN EUROPE (incl.USSR)	635.2	797.7	959.9	1089.9
- USSR	582.4	743.7	914.6	1050.8
- East. Europe (excl.USSR)	52.8	54.0	45.3	39.1
AFRICA	55.5	77.1	100.9	116.7
MIDDLE EAST	69.8	91.6	109.0	126.6
ASIA / OCEANIA	103.9	152.5	183.8	210.4
- Japan, Australia, New Zealand	17.9	23.5	31.2	32.8
- Others	86.0	129.0	152.6	177.6
WORLD	1,617.9	1,904.3	2,218.9	2,324.5

In Eastern Europe, excluding the USSR, most of the production is located in Romania, and there is little prospect that this country can sustain current level of production. There is some prospect for improved production for some of the other countries in the region, as in the case of Yugoslavia. On the whole, these countries will experience a decline, from about 53x10^9 m^3 in 1985 to about 39x10^9 m^3 in 2000.

For the USSR, the development of its proven resources, growth in production and the existing large extensive gas pipeline somewhat favour the further development of the country's gas resources, especially the development of giant gas fields, such as Urengoy and Yamburg and in time, those in the Yamal Peninsula. On the whole, USSR production could grow on the average of 4% annually, and reach a level of 1,150x10^9 m^3 in 2000.

In the Middle East, a modest domestic market for gas, and the presence of large associated gas production, limit the prospects of some of these countries; but Qatar and Iran will seek to use more of their significant gas reserves to meet regional needs and for export. Production in this region may reach 127x10^9 m^3 in 2000.

In Latin America, growth in gas production is constrained more by the lack of a gas transport and distribution infrastructure than by a lack of reserves. Nevertheless, the need to eliminate waste associated with the large production of gas, primarily in Mexico and Venezuela, and the development of some other gas markets in the region, notably Argentina and Brazil, should sustain growth in production, reaching about 126x10^9 m^3 in 2000.

The Asia/Oceania region, the report concludes, is the world's most dynamic region relative to growth in reserves and production. There are sharp contrasts in the region, however, between countries endowed with large gas desposits, such as Australia, Brunei, Indonesia, Malaysia and Thailand, and countries which are virtually lacking in indigenous gas resources, as Japan, the Republic of Korea, Taiwan and Singapore. The region as a whole, however, in spite of the diversity among countries in the region on the state of economic development, favours continued growth in the production to satisfy domestic markets and interregional gas trade. Production in the region could reach a level of about 210x10^9 m^3 in 2000.

9. ENVIRONMENTAL IMPACTS, RISK HAZARDS AND HEALTH ASPECTS OF NATURAL GAS PRODUCTION AND TRANSMISSION SYSTEMS

9.1. Production

Exploration and production of natural gas involves activities quite similar to those for crude oil, and their impacts on the environment, to a certain degree, are quite similar. Sites must be prepared to carry out the drilling, fluids discharged during drilling must be disposed of, gas processing plants may discharge undesirable affluents, etc. Most countries have adopted measures to control such operations and the industry itself generally adheres to sound operating practices. Unlike crude oil, there is no spillage problem with gas. In the offshore, where production platforms often produce both oil and gas, failure of those facilities can result in the discharge of the crude oil and natural gas but, again, the damage from a liquid discharge (oil) is quite more significant and different than for gas.

Natural gas, as produced at the well, contains not only hydro- carbons but also impurities, as noted elsewhere in this report. Some of these impurities are highly toxic and corrosive and are removed prior to the gas being delivered to a gas pipeline or directly to a consumer.

Gas processing technology can remove close to 100% of the sulphur present in natural gas but the availability of such technology is not always readily available to some countries.

Some natural gas production results in a certain volume of gas flared or vented to the atmosphere, due to a lack of market for the gas, delays in being connected to a gas gathering/gas pipeline system or the need to produce oil, as is often the case with the associated/dissolved gas. There is a lack of reliable data to assess the extent of such emissions to the atmosphere.

CEDIGAZ estimated the amount of flared gas world-wide to be 3.9% of the gross production, or 92.4x10^9 m^3 [5]. Flaring is more pronounced in some countries than others, especially where there is a large production of associated/dissolved gas with the production of crude oil. Such flaring has been reduced sharply in recent decades, as most countries consider it a waste of a valuable natural resource. OPEC producers, for example, accounted for 49% of the volume flared in 1988, whereas in 1973 it was 76% of the world's total. This reduction is due, to a large extent, to measures adopted by these countries to recover the gas.

9.2. Gas Transmission and Distribution Systems

The placement in service of gas pipelines distribution systems has a minimal impact on the immediate environment since they are generally buried underground, with the exception of Arctic conditions, where it may require above-ground installation. This poses certain risks to the gas pipeline network and in natural gas leakage from accidents breaking the pipeline. There is a vast network of gas pipes buried in the ground in the world, found predominantly in North America, Western and Eastern Europe. Some of those pipes and distribution systems have been in service for some decades but some are relatively new. The operation of these extensive systems leads to some degree of gas leakage. There is much speculation as to the extent of such leakage. Some observers suggest that "unaccounted for gas", noted in some gas industry statistics, represent lost gas, but this generally is not the case. It is often due to poor metering and to statistical accounting to balance supply with consumption. Some published data may also include gas used by pipelines as fuel, which is not "lost" gas. The same study concluded that methane losses in other Western gas markets were less than 1%. Recently, because of the problem associated with methane as a "greenhouse" gas, some attempts have been made to quantify such leakage for the world gas industry. The American Gas Association estimates that no more than 5% to 8% of the world's emissions of methane is derived from the gas industry, and that its contribution to the "greenhouse" effect is not more than 1% to 1.5%. More recent estimates [9] suggest that methane released from gas transmission systems range between 0 and 0.13%. It is slightly higher for gas distribution systems, 0.03% to 0.3% for newer systems and up to 1% for older systems. There is growing awareness on the part of the gas industry and interested governmental and non-governmental institutions to develop more reliable data to deal with this issue.

The International Workshop on Methane Emissions from Natural Gas Systems, Coal Mining and Waste Management Systems, held in Washington, D.C., in April 1990, concluded that methane emissions from the gas industry of the United States, Canada, Japan and Western Europe, which accounts for 44.5% of the world's gas consumption, is likely to be less than 1% and that global emissions are in the range of 25 - 45 million metric tons (mmt) per year. The workshop further concluded that uncertainties exist about the methodology employed in making such estimates and for its dimensions worldwide. Key uncertainties that need to be addressed are:

- emissions from abandoned and old wells;
- post-metering emissions;
- emissions from gas systems in Eastern Europe, the USSR and developing countries;
- how representative the systems are upon which preliminary estimates are based.

The extent to which more precise data will be available to increase the reliability of current estimates on methane emissions associated with gas production and gas transmission/distribution is a challenge for the gas industry. Given the presence of many players in the world gas industry, its different state of development, and diversity in ownership and operating practices, it is questionable whether precise statistical information can be developed.

At best, more precise estimates can be developed selectively by countries which are currently engaged in studying this problem. This could lead to improved measuring and calculating techniques to develop better world-wide data. This has been done in Germany where careful studies of methane emissions from gas operations indicate that less than 0.7% of the natural gas used in Germany escapes [14].

Besides the gas industry, there are a number of other activities that contribute significant quantities of methane. The workshop noted above concluded that coal mining activities emit about 30 - 50 mmt per year, with some estimates being as low as 20 mmt and as high as 60 mmt. These emissions are roughly 7% of the global methane emissions and about 10% of the global anthropogenic sources of methane. Waste management systems, which include land- fills, animal waste and waste water treatment facilities, are also major sources of methane. From landfills global emissions are in the range of 25 - 40 mmt per year; animal waste 20 - 40 mmt, and water treatment facilities 20 - 25 mmt.

9.3. End-Use of Natural Gas

Natural gas, as delivered to the consumers, is a versatile source of energy. The primary constituent, methane, can be used as a fuel in power plants, in industry, or in the domestic and commercial sector for cooking, heating, etc. It can also be used as a feedstock for the production of ammonia, urea, fertilizer and methanol. Indications of the diverse use of gas are shown in Fig. 12. Natural gas offers a number of advantages over alternative fuels. It is cleaner burning, a quality recognized in manufacturing and industrial applications where avoiding product contamination is critical. Gas also provides a higher energy per unit of output compared to oil and coal, and gas burners can control the temperature of a flame better than burners for the other two fuels.

It is because of those qualities and characteristics that natural gas is considered "environmentally" friendly.

Before examining the emission levels of gases of combustion originating from oil, coal and natural gas, a comparison of these three energy sources will provide an insight as to why coal and oil give rise to disproportional levels of undesirable by-products, compared to natural gas [10]. Table IX illustrates the impurities, such as sulphur, nitrogen and other substances present in natural gas, oil and coal. Natural gas has substantially fewer impurities, such as sulphur, combined nitrogen, and a host of other substances. With available technology, many of these substances can be removed from coal and oil products but at a substantially higher cost than for natural gas. As noted earlier, gas delivered to consumers is quite clean and does not require the technology and costs associated with the other two fuels to remove such impurities. During combustion, the absence or virtual lack of sulphur means negligible sulphur oxide emissions [12], as illustrated in Table X.

Table IX Inpurity content of various fuels

	Natural gas	Oil	Coal
Ash	-	< 0.4 %	7-20 %
Sulphur	10 ppm	0.1-0.4 %	0.5-2.5 %
Combined nitrogen	-	-	1-2 %
Chlorine	-	-	up to 0.6 %
Other inorganic trace metals	-	-	5-20 mg/MJ
(Unit: mg/MJ)			
Arsenic	< 0.00003	0.5-2	30-2,900
Cadmium	< 0.04	0.2-0.7	400
Cobalt	-	-	30-1,600
Mercury	< 0.004	0.9-0.16	400
Chronium	< 0.03	0.6-1.2	120-1,300
Manganese	-	-	400-1,200
Nickel	-	-	320-3,200
Lead	< 0.006	3.0-25	1,200-4,000
Vanadium	< 0.003	2-1,300	321-6,000
Zinc	< 0.003	2-20	1,200-3,000

Environmental Aspects in End-Use, proceedings of the Symposium on the Gas Industry and the Environment, Committee on Gas, Economic Commission for Europe, October 1986

Table X Some representative SO_2 emissions per unit of energy

Fuel	Sulphur Content (%)	Calorific Value (MJ/kg)	SO_2 Emissions (mg/MJ)
Coal	1	25	720
with FGD			72
Heavy Sulphur Coal	3	25	2,200
with FGD			220
Heavy Fuel Oil	3	42	1,400
with FGD			140
Fuel Oil	1	42	480
with FGD			48
Gas Oil	0.3	43	140
Natural Gas	0.002	53	0.73

FGD - Flue Gas Desulphurization. For the SO_2 emissions of fuels by technologies using FGD it is assumed that 10% of sulphur remains in ash.

Note: There is a wide range between emissions of different qualities of coal and oil. SO_2 emissions (g/GJ) of coal burning may vary between 350 and 3,200 and of oil combustion between 70 and 700. This explains why in some countries substantial emission reductions have been achieved through a switch to low-sulphur coal or low-sulphur oil.

One emission during combustion which natural gas shares with oil and coal is nitrogen oxides (NO_X) [11], but even here, as shown in Table XI and Fig. 13, emissions of NO_X is substantially less than for coal and oil. Unlike sulphur emissions, which to a large extent are controlled by abatement measures, emission of NO_X is more complex. Emissions in this case are a direct product of combustion and their emissions are quite sensitive to combustion temperatures and the presence of air. Increases in combustion temperatures are likely to increase NO_X emissions but control methods exist or are being developed, such as modifications of combustion burners or limiting the amount of oxygen (air).

Table XI Carbon dioxide emission from the direct combustion of various fuels

Fuel	CO_2 emission rate (kg C/GJ)	Ratio relative to methane
Methane	13.5	1
Ethane	15.5	1.15
Propane	16.3	1.21
Butane	16.8	1.24
Gasoline	18.9	1.40
Diesel Oil	19.7	1.46
No. 6 Fuel Oil	20.0	1.48
Bituminous Coal	23.8	1.73
Sub-bituminous Coal	25.3	1.87

Source: OECD, "Energy Technologies for Reducing Emissions of Greenhouse Gases", Proceedings of an Experts' Seminar, OECD, Paris, April 1989

A more recent environmental problem associated with the consumption of fossil fuels is the release of CO_2, one of the gases identified as being a contributor to the "greenhouse effect". Methane released during the production and transmission of natural gas has also been identified as a contributer to the green-house effect. There is speculation and uncertainty associated with the levels of emissions of various gases and their impact on the greenhouse effect. The same holds true for natural gas as a source of methane or CO_2. During combustion, the degree of emissions of CO_2 from natural gas is also less than for oil and coal. This is due to the relative higher carbon content in coal and oil versus natural gas (Fig. 14, Table XI). The combustion of low-carbon natural gas gives rise to less CO_2 than from oil and coal [12] (Fig. 15). A substitution of natural gas for these other fuels is one available measure to reduce CO_2 emissions.

Regarding methane emission and its impact on the "greenhouse" effect, much remains to be done to arrive at more precise estimates of the various sources of methane, including emissions from gas industry operations, as noted elsewhere in this report.

It is beyond the scope of this paper to review and discuss in detail the relationship between natural gas and the environment, including climate change, and energy production and use in general. Extensive work has been carried out in this area, foremost of which is the work of the Intergovernmental Panel on Climate Change (IPCC) of the World Meteorological Organization and the United Nations Environmental Programme.

The IPCC has dealt with a number of issues and problems associated with emission of gases, including methane.

Regarding energy, the IPCC stated:

"We note that energy production and use account for nearly half of the enhanced radioactive forcing resulting from human activities and is projected to increase substantially in the absence of appropriate response actions. We recognize the promotion of energy efficiency as the most cost-effective immediate measure, in many countries, for reducing energy-related emissions of greenhouse gases, [in particular CO_2] while other [safe] options such as no or lower greenhouse gas emitting energy sources should also be pursued. These principles apply to all energy sectors." [13]

Although the Panel did not specifically endorse natural gas as one fuel option to reduce emissions, it is nonetheless implied in the above statement, calling for " ... lower greenhouse gas emitting energy sources ... ".

10. CONCLUSIONS

Favoured by a large resource base and its rate of development and production in recent decades, there is every reason to be optimistic about the future availability of gas supply to satisfy world requirements. International gas trade has increased in response to growing requirements for gas. No technical constraints exist to move gas supplies to markets although economics will influence such trade, given the relatively high investments for gas trade projects and the need for long-term stability of energy markets.

Most markets in the world, recognizing the need to secure long-term sources of supply, have taken measures to develop their indigenous gas resources and to secure imports. Diversification of supplies by source will continue to guide gas enterprises and governments in countries where imports are likely to remain a major source of their gas supplies.

Environmental factors identified with the production and use of fossil fuels have clearly shown that natural gas is benign to the environment, although the gas industry should take initiatives and measures to deal more effectively with the emission of methane from gas industry operations.

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ANNEX 1

Physical and Chemical Characteristics

Natural gas is a naturally occurring substance, found in geological structures similar to those containing crude oil. As produced at the wellhead, it is a mixture of hydrocarbons and non- combustible gases, with methane being the predominant hydrocarbon. Natural gas delivered to the consumers is essentially all methane, with some ethane included to provide an acceptable heating value for various end-users and applications.

Other hydrocarbons present are primarily ethane, propane and butane, which are recovered in gas processing plants, along with non-combustible gases, and the hydrocarbons become a major source of liquefied petroleum gases (LPG), along with similar products recovered at refineries. LPG, besides being a feedstock for the petrochemical industry, is also used as a gaseous fuel where natural gas is not available. Natural gas, as delivered to gas pipeline/distributions systems and to other end-users, must meet rigid quality standards regarding the presence of impurities, such as carbon dioxide, notrogen, sulphur, water, etc. These standards are normally contained in gas purchase contracts or tariffs.

To distinguish the origin of gas production, there are two main categories:

- Associated gas: natural gas recovered from reservoirs where the gas is found dissolved in crude oil or in contact with gas saturated crude oil (gas-cap/gas).

- Non-associated gas: natural gas produced from geological structures or from condensate reservoirs, which yield relatively large amounts of gas per barrel of light liquid hydrocarbons (condensate).

- End-uses of natural gas: Natural gas is used predominantly as a fuel, for heating, cooking and other applications generally identified in principal categories, such as

- Domestic/commercial sector: for space heating, cooking, water heating.

- Industrial sector: as boiler fuel for steam generation, large heating requirements and various industrial and manufacturing processes, especially where a "clean" fuel is required, such as ceramics, glass-making, etc.

- Electric power sector: used for base-load electric power generation and, recently, increasingly for combined-cycle power and co-generation.

- Petrochemicals: used as feedstock for the manufacture of ammonia and methanol.

- Other uses: a small market has developed to use compressed natural gas (CNG) as a vehicle fuel. Other uses that have some market potential are fuel cells, gas-to-gasoline or gas-to-middle distillates conversion.

ANNEX 2

Unconventional Gas Resources

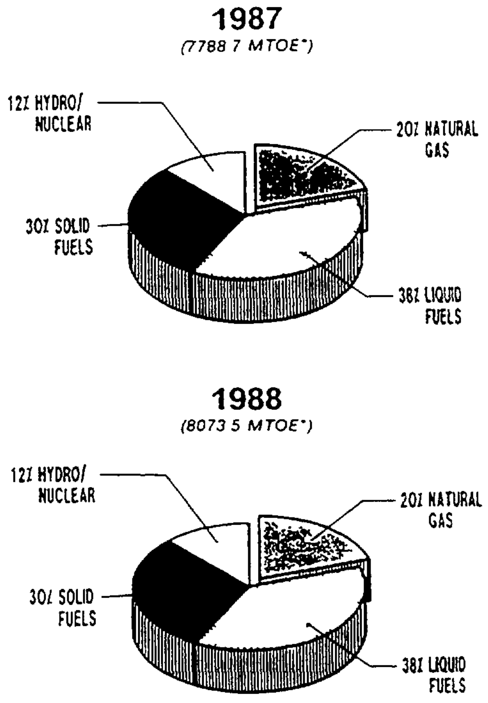
1. Tight gas, or tight sands gas, is natural gas that is found in rock formations of extremely low permeability. It is characterized by slow rates of production. Wells drilled in these formations generally are stimulated to increase flow rates, by artificially fracturing the rock around the wellbore. Tight gas formations are known to exist in gas producing basins in a number of regions of the world.

2. Devonian shale gas is natural gas found in the fractures and pore spaces and absorbed (bound) to the physical structure of shales deposited during the Devonian period of geologic time. They exist in a number of basins in the Appalachian, Illinois, USA, and fractures in the shale provide critical flow pathways for production, but the low permeability of both the shales and the natural fractures generally must be overcome with artificial fracturing of other stimulation techniques.

3. Coal-bed methane is natural gas created as part of the coal formation process. It is found predominantly in the form of gas absorbed to the coal itself, but also as free gas in the pores and fractures of the coal. As with Devonian shale gas, the natural fracture system plays a critical role in production. Also playing a key role is the water often found in the coal seam, as the water must be removed before gas can "desorb" from the coal and flow to the well.

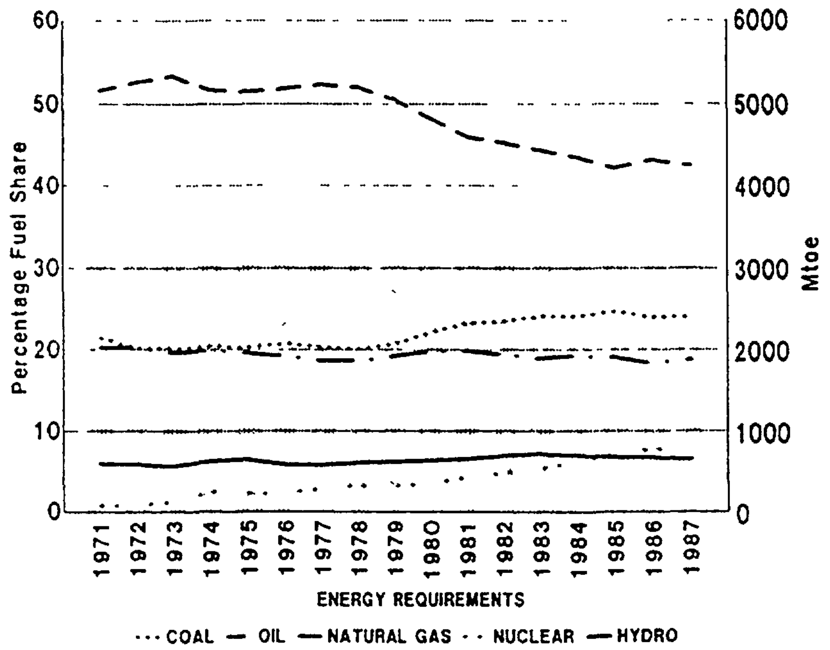
4. Natural gas from geopressurized aquifers is gas dissolved in brines deep within the earth under high pressures and temperatures, found primarily in the gulf coast region. In order to produce the gas, the brines are pumped to the surface, the gas removed, and the brines disposed of.

5. Gas hydrates are an ice-like mixture of gas and water, called a "clathrate" that forms under certain temperature/pressure conditions often found under water depths greater than 100 feet and under permafrost. The resource is potentially huge, and may be augmented by free gas trapped under the impermeable hydrate. At this time, all proposed production methods are highly speculative.



* Million tons of oil equivalent
Source BP Statistical review of World Energy - July 1989

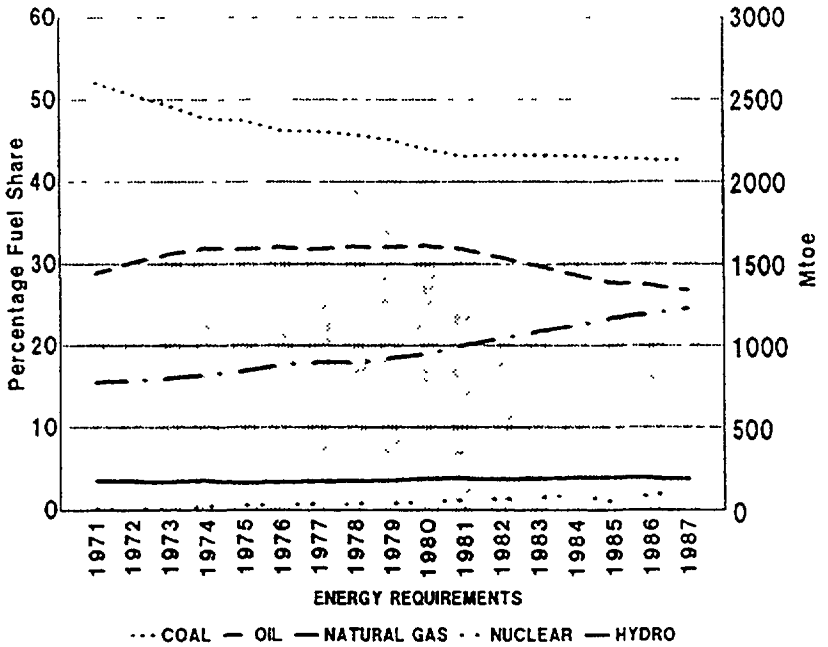
Fig. 1 World primary energy consumption



* *Mtoe* Million Tons of Oil Equivalent

Source: *"World Energy Statistics and Balances 1971/1987"* OECD, Paris, France, 1989

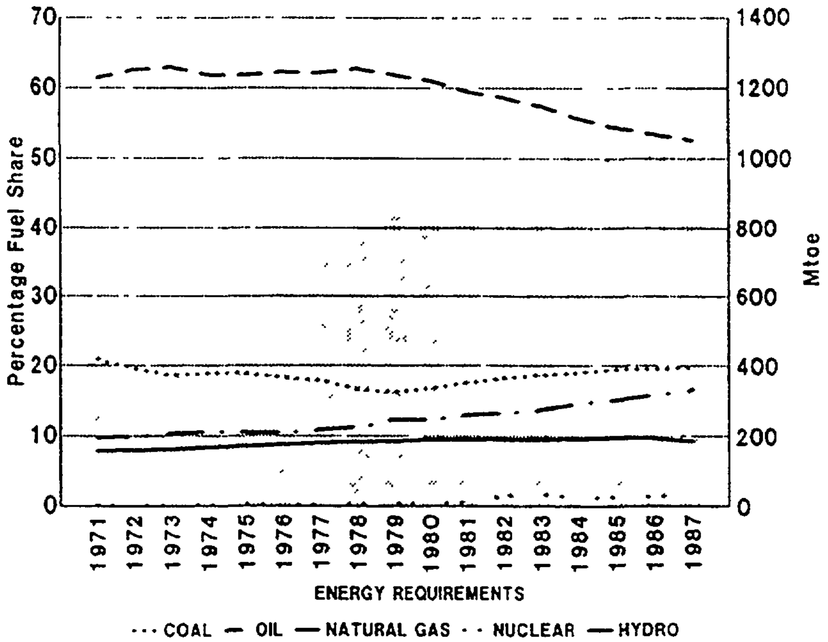
Fig. 2 OECD Energy requirements by fuel and as percentage of total (mtoe)*



* *Mtoe* Million Tons of Oil Equivalent

Source "*World Energy Statistics and Balances 1971/1987*"OECD, Paris, France, 1989

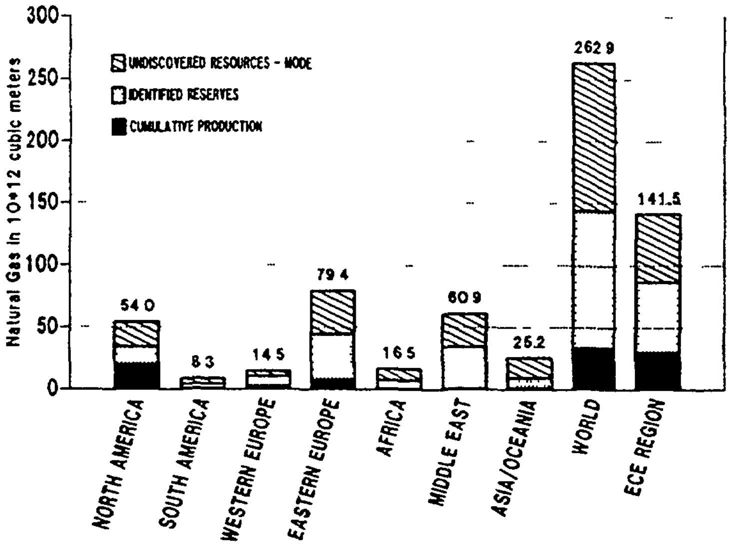
Fig. 3 CPE's Energy requirements by fuel and as percentage of total (mtoe)*



* *Mtoe* Million Tons of Oil Equivalent

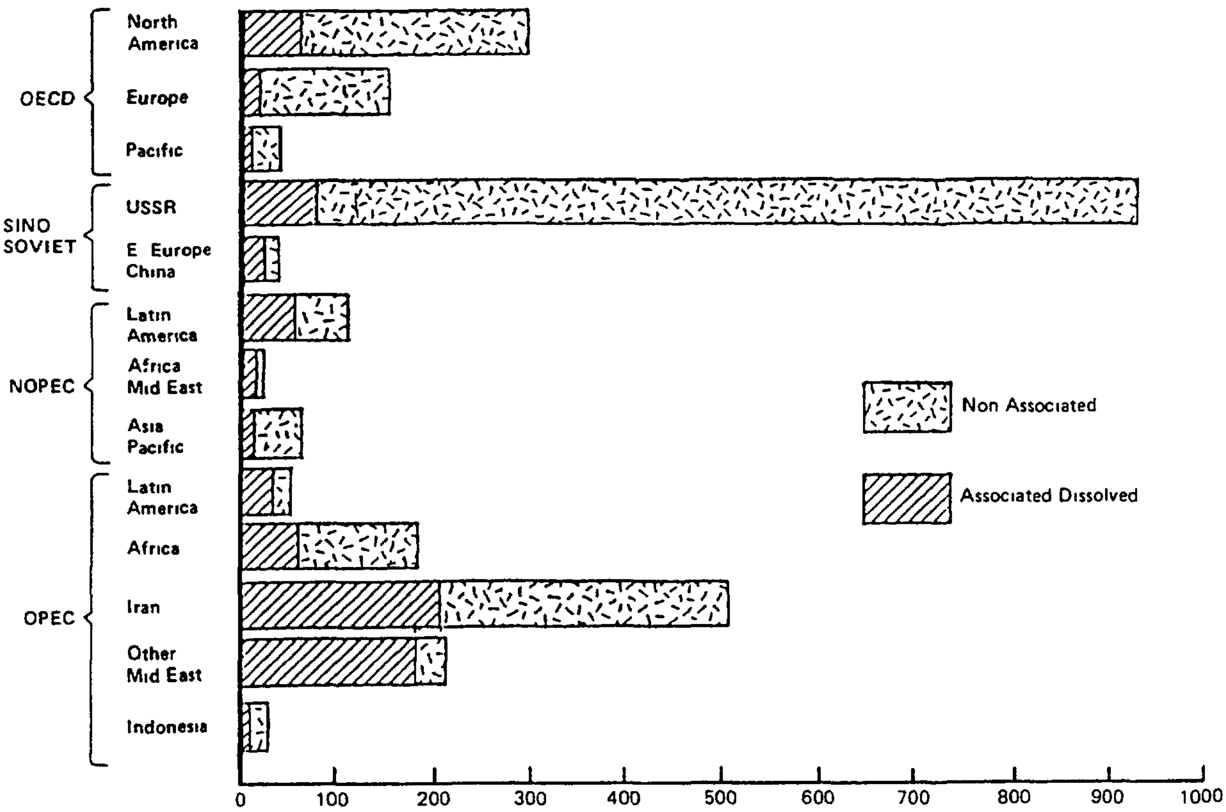
Source "*World Energy Statistics and Balances 1971/1987*"OECD, Paris, France, 1989

Fig. 4 Developing countries energy requirements by fuel and as percentage of total (mtoe)*



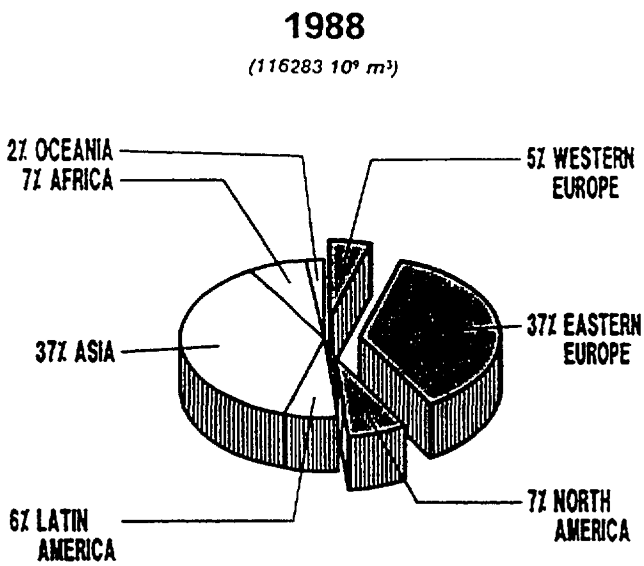
Note Regional distribution of identified reserves and cumulative production of natural gas as of 1/1/1985 and mode of undiscovered resources as of 1/1/1985 Original units in cubic feet were converted to cubic meters using the conversion factor 1 cubic meter = 35 3 cubic feet

Fig. 5 World estimate of original reserves and ultimate recoverable resources of conventional natural gas



Source World Natural Gas Reserves and the Potential for Gas Trade by James T Jensen Jensen Associates Inc

Fig. 6 World natural gas reserves (10^{12} ft^3)



Source: CEDIGAZ - Natural Gas in the World in 1988.

Fig. 7 World proven natural gas reserves at year's end

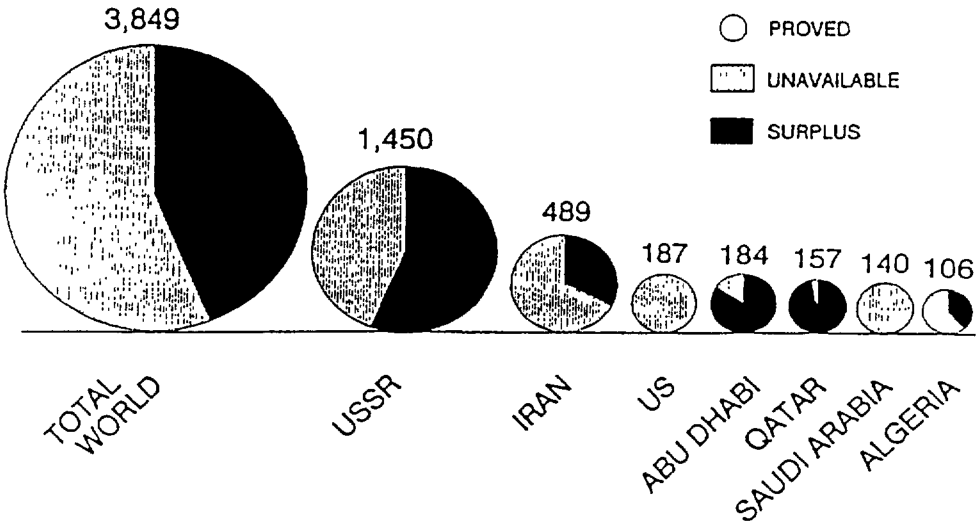
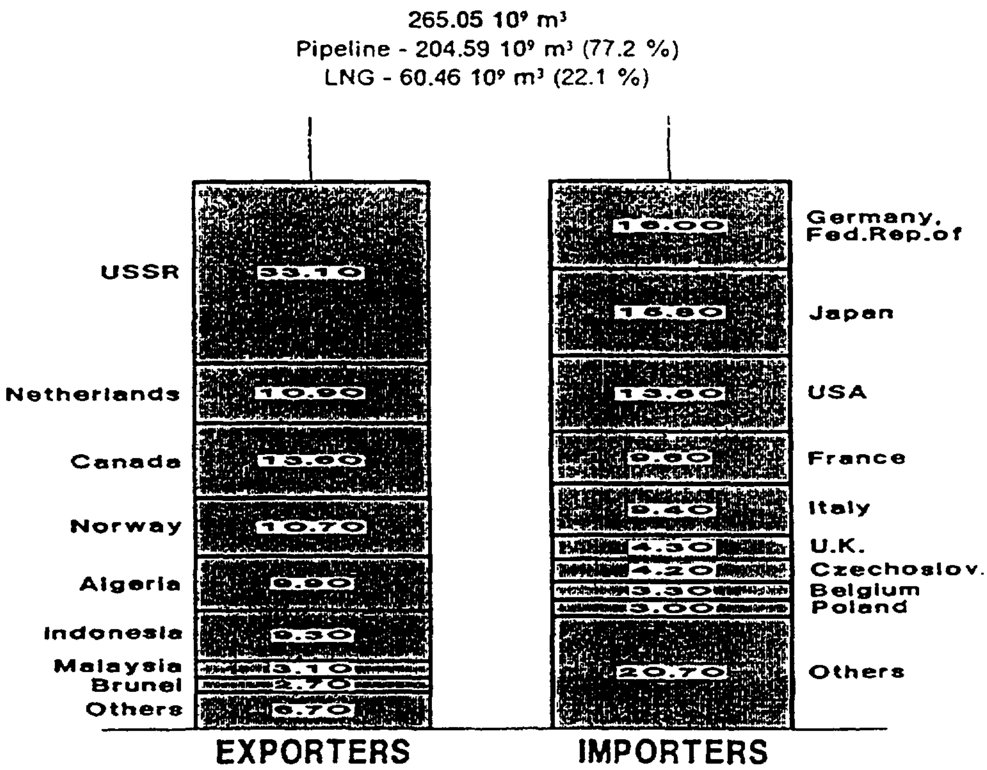


Fig. 8 Proven gas reserves and exportable surpluses, December 31, 1987 (10^{12} ft^3)



Source: CEDIGAZ-Natural Gas in the World in 1988.

Fig. 9 World natural gas trade in 1988 (percentages)

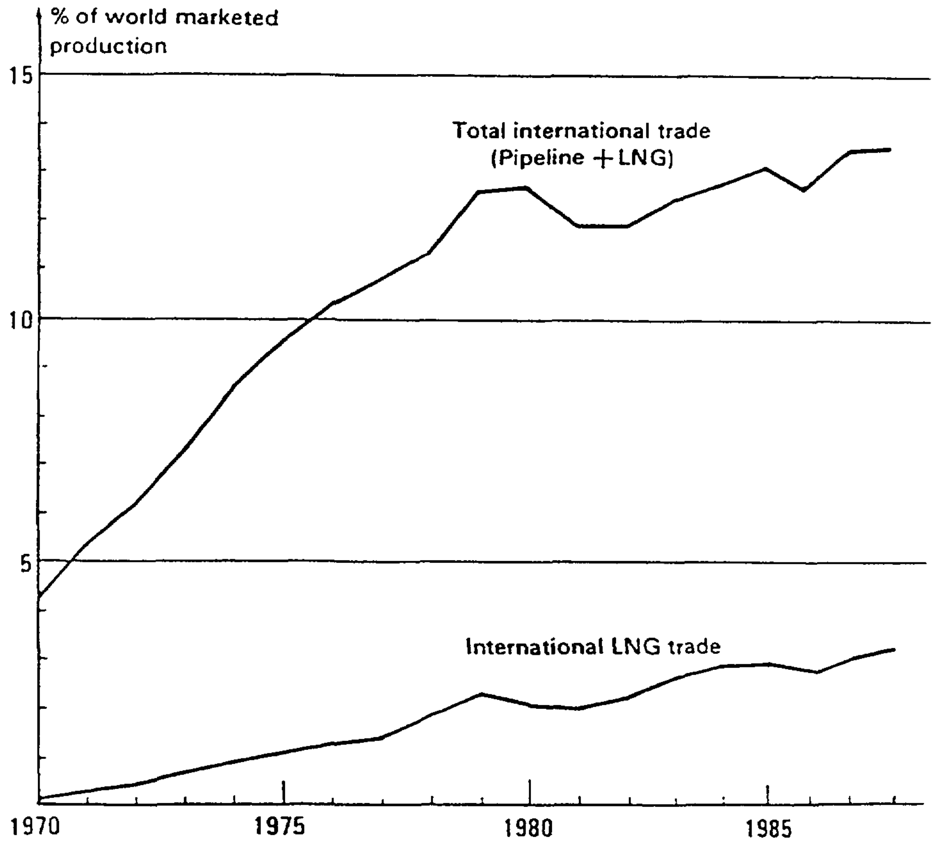
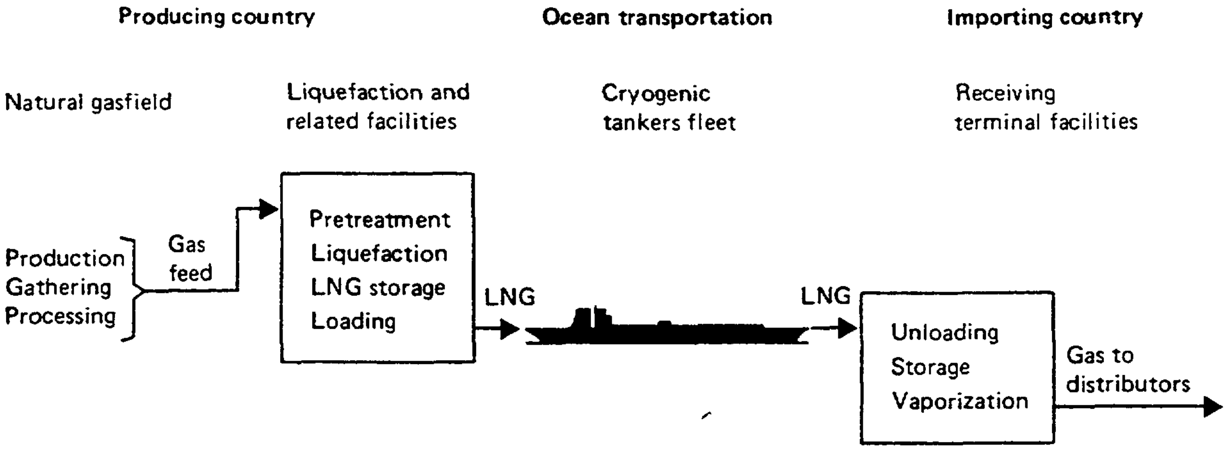


Fig. 10 Share of international gas trade in world marketed production



Source: Jensen Associates, Inc.

Fig. 11 Major segments of LNG Import project

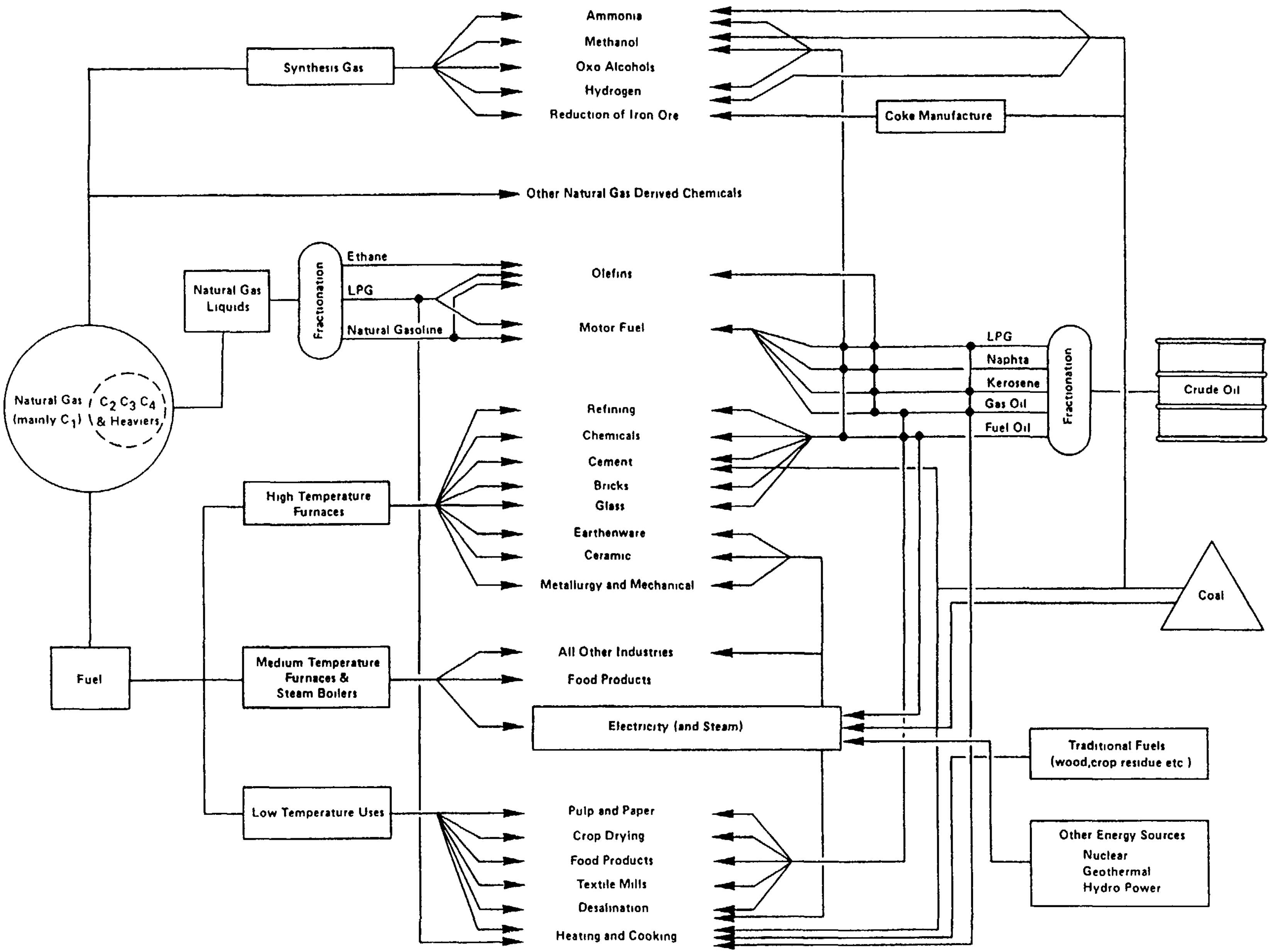
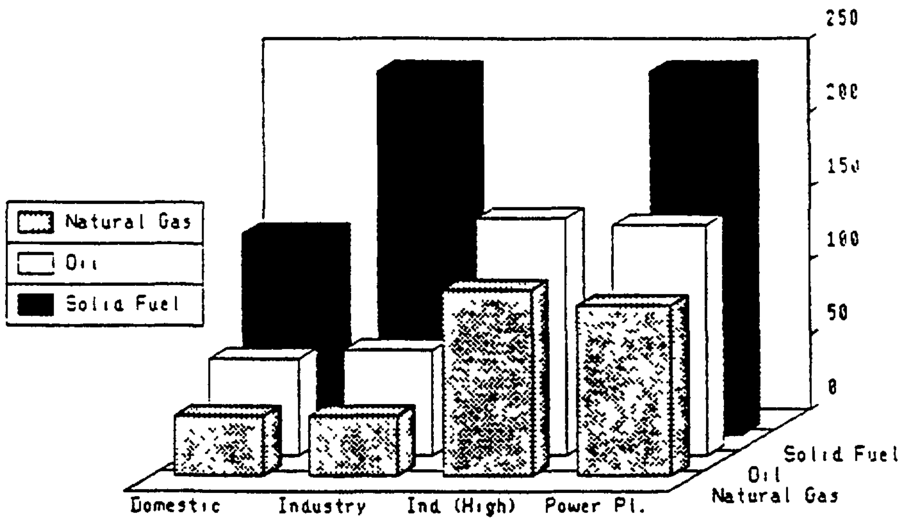


Fig 12 Natural gas, its use and competitors



(1) Use of SCR may reduce these NO_x emissions by 80-90% and use of low-NO_x burners by about 50%. Note that these factors can vary by two to three orders of magnitude depending on combustion conditions.

Fig. 13 Nitrogen oxide emission factors (1), (Emissions per unit of energy)

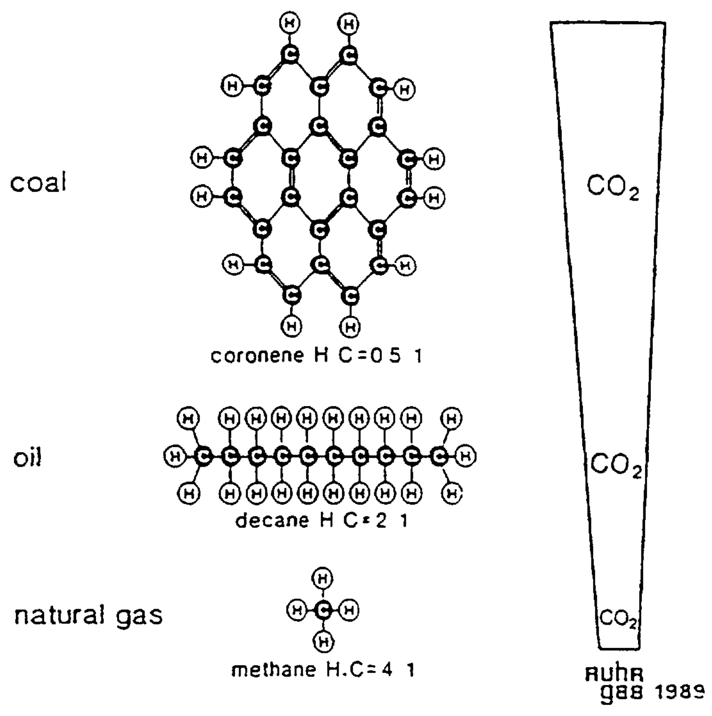


Fig. 14 Hydrogen/carbon ratios and CO_2 formation by fossil fuels

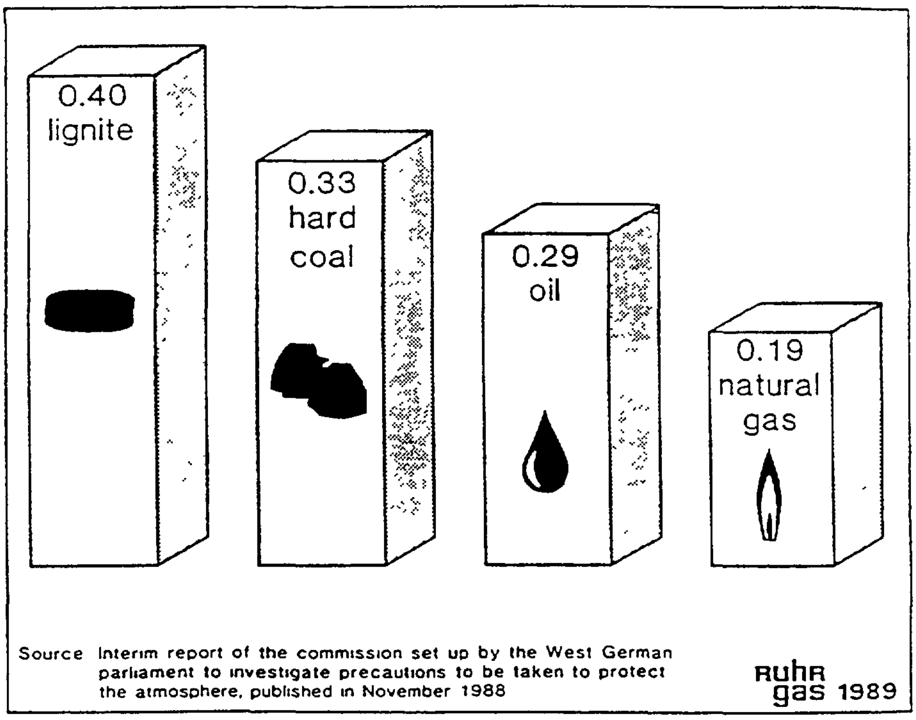


Fig. 15 CO_2 formed by the combustion of fossil fuels (kg CO_2/kWh fuel input)

ELECTRICITY GENERATION FROM WASTES

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ABSTRACT: Waste can be used directly for electricity and district heat generation in waste heat incineration plants but also indirectly by burning the offgases from landfills. Appropriate technologies for both possibilities of waste use are already available; in the case of landfill gas already economically.

Based on the waste production within the OECD countries in the late 1980s of about 420 million tons of municipal waste and about 1,400 million tons of industrial waste, a theoretical energy potential can be calculated which corresponds to about 8% of the annual energy consumption within OECD. In fact, less than 1% of the total energy demand is satisfied by waste.

Besides of sulphur dioxide, nitrogen oxides and particles which are of most importance in the case of fossil fuels, energy from waste produces hydrogen chloride, hydro-carbons, like polycyclic aromatic and especially chlorinated ones, like dioxins and furans, and furthermore also heavy metals, like cadmium and mercury. Greenhouse gases, like carbon dioxide, are also emitted from waste treatment but are of lesser importance than in the case of fossil fuels.

Energy supply from waste will only play a limited role in future energy systems mainly because of the preferences for waste reduction and recycling within future waste management strategies. Furthermore, landfilling of waste cannot be regarded as an appropriate strategy because of the long term environmental risks. The already low energy efficiency for waste incineration will decrease further because of increasing demands for offgas cleaning and ash treatment.

1. INTRODUCTION

Among the renewable energy sources also the use of waste as fuel for different burning facilities (incineration-plants, boilers, combustion engines) in form of solid waste as direct fuel and offgases from landfills is discussed, despite the fact that waste is no renewable energy source in the strong sense.

In some countries, like the Federal Republic of Germany (FRG), waste incineration contributes with 2 TWh about 0.6% to the total electricity production and in this sense is the second important renewable energy source following water power, which contributes with 14 TWh about 4% to the total electricity production. In chapter 2, the possible contribution of waste to total energy supply is presented.

The state of current and future technology is exemplified by model facilities in chapter 3.

In chapter 4, three sets of specific effluent values are presented for the years 1990, 2000 and 2020.

Finally in chapter 5 a general evaluation of the possibilities of landfill gas burning and waste incineration to total energy supply is given.

2. POSSIBLE CONTRIBUTION OF WASTE TO TOTAL ENERGY SUPPLY

In all industrialized countries there is still a tendency towards increased waste production. Within the OECD countries there was an increase in municipal waste production from about 340 million tons in 1980 to about 420 million tons in late 1980s [1]. Besides this in the OECD there was an amount of 1,400 million tons of industrial waste in late 1980s. Based on these values a theoretical energy amount of about 14,200 PJ can be calculated, which is more than 8% of the annual primary energy consumption within the OECD countries with about 170,000 PJ.

In some countries like the FRG about one third of the municipal waste is burned, contributing 0.6% to the total electricity production. If all municipal waste would be burnt, nearly 2% of electricity supply could be satisfied; this contribution could still be enlarged by burning industrial waste. The contribution of waste incineration to total energy supply is still larger as most of the facilities are co-generation plants, producing also district heat besides electricity. Assuming the same efficiency for the generation of district heat as for the generation of electricity, the total contribution of waste incineration to future energy supply could theoretically arrive at 5 to 10% under optimal conditions.

There is no information available about the world total installed capacity of incineration plants at present and the expected development. Therefore a rough calculation for the present situation was made on the basis of the total waste amounts generated [1] and percentages of waste incinerated in some industrialized countries [2]. This calculation, regarding Denmark, France, FRG, Italy, Japan, Netherlands, Sweden, Switzerland, United Kingdom and the United States of America, results in 80 million tons of waste incinerated per year (reference years 1984/85/86), yielding a total energy output of about 680 PJ on the basis of a waste heating value of 8.5 MJ/kg.

Assuming 7,000 hours operating time per year for the plants, a total installed thermal capacity of about 27,000 MW can be calculated. If the conversion efficiency for electricity generation is 18%, a total installed electric capacity of 4,900 MW could be derived at. As most of the plants are operated in the co-generation mode, this capacity doubles when district heat production is considered in addition.

As there is a tendency in most industrialized countries for increased waste incineration, the installed electric capacity will roughly double by the year 2010 to about 10,000 MW.

Landfill gas utilization is another possibility of using energy from waste. In 1987, about 150 commercial facilities were in operation in a total of 15 countries [3]. Nearly 80% of these facilities are located in the FRG, UK and the USA. The preferred ways of energy exploitation are the

- generation of electricity using engines (56 facilities),
- burning in boilers (33 facilities),
- purification for main pipeline distribution or
- use as a vehicle fuel.

It is estimated that these projects save at least 825,000 tons of coal or 24.2 PJ per year. Total global electricity output from landfill gas fuelled installations is estimated at 170 MW_e for the year of 1987, to which the USA contributes about 150 MW_e and both the UK and FRG about 10 MW_e each [3].

As the utilization of landfill gas is a relative simple technology, a doubling of the world total installed capacity to about 400 MW was assumed for the year 2000. Until 2010 this capacity is expected to increase to 600 MW and to remain at that level thereafter.

3. CHARACTERISTICS OF PLANTS FOR ENERGY GENERATION BY WASTE

3.1 Waste incineration plants

There is a wide variety of capacities for waste amount of existing waste incineration plants ranging from 2 to 80 t/h, with a typical value between 15 to 60 t/h. Given an average operation time of 7,000 hours per year, a total amount of waste between 100,000 and 400,000 t per year will be burnt in these facilities. The waste heating value also varies between 7 and 11 MJ/kg with increasing tendency because of the increasing share of plastics in the waste. Assuming a heating value of waste of 8.5 MJ/kg and an efficiency for electricity generation of about 18% – reference is made to the waste incineration facility in Essen-Karnap/Germany [4] – installation capacities for electricity generation between 6 and 25 MW_e can be calculated.

An important fact for the evaluation of waste incineration in total energy supply is that most incineration plants are operated as co-generation plants, generating not only electricity but also district heat. In refernce to Ref. [4], an average efficiency for heat generation of about 20% can be assumed, yielding an overall total energy conversion efficiency of about 38%.

The construction time for incineration plants is about 3 years. According to the need for continuous waste management an operating time of about 7,000 hours per year has to be achieved.

Regarding the costs of the incineration plants, in particular capital and operation and maintenance (O&M) costs, it must be pointed out that it is not the primary purpose of these facilities to produce energy but to treat waste in such a way that the residues from the incineration can be deposed with minimal risk for the environment. Furthermore it must be regarded that these facilities are mostly operated in co-generation mode, generating not only electricity but also producing district heat. Therefore all calculated values can have more demonstrative character and they are given in relation to electricity and district heat generation (e + dh). For medium size facilities in the range of 200,000 t per year (respectively 30 t/h) capital cost vary from DM 8 to 10 per t/h [5]. Relating to electricity and heat capacity installed values in the range from DM 9 to 11.3/W (e + dh) (US $5.3 to 11.3/W(e + dh))[1] can be calculated.

Of special interest are O&M costs, for which in the regarded sizerange values from DM 200 to 250/t of waste are given [5]. Based on such values, O&M costs between DM 0.23-0.28/kWh (e + dh) (US $0.13-0.17/kWh (e + dh)) can be derived. It needs to be stressed again that these values have only theoretical importance, because the main task of waste incineration is waste treatment and not energy production.

3.2 Landfill gas facilities

The natural bacterial decomposition of organic materials in the absence of oxygen results in the production of a methane rich biogas, called landfill gas. This gas is composed primary of equal parts of methane and carbon dioxide, with trace organic chemicals, e.g. benzene, trichlorethylene, vinyl chloride, methylene chloride. Methane production begins once conditions in a landfill become anaerobic. Rates of methane production depend on moisture content of the landfill, concentration of nutrients and bacteria, pH, age and volume of the degrading material.

The theoretical volume of gas, based on the carbon content of average composition of municipal waste, assessed by several authors was estimated at about 400 m^3/t [6]. Actually a much lower gas amount can be used, varying between 120 and 250 m^3/t [7]. For the rate of gas production a value between 1 and 15 m^3/t per year was found. Within the first years a rough value of about 10 m^3/t per year can be assumed. This value will also be used in the calculations of this report. After a period of about 20 years the gas production will decrease to less than 1 to 2 m^3/t per year. The methane content of landfill gases is varying between 50 to 55%; a content of 50% will result a heating value of 18.6 MJ/m^3. For this report a value of *18 MJ/m^3* was selected as average for calculation purposes.

In principal, there are four possibilities for using the landfill gas

(1) to generate electricity using internal combustion engines,
(2) to generate electricity and heat from burning in boilers,
(3) to purify for pipeline distribution and
(4) to purify for use as vehicle fuel.

Regarding the existing facilities, there is a strong preference for alternative (1) generation of electricity using internal combustion engines. Therefore such a facility was chosen

[1] *Exchange rate: 1.7 DM = 1 US $*

as a model facility for the purposes of this investigation. At the smaller scale of up to 1-2 MW output internal combustion gas engines are preferred for heat and electric current generation, at multi-megawatt outputs gas turbines are also used. In the FRG facilities are generally smaller than those in the UK or the USA. The average facility size in the USA is about 2.3 MW (largest planned facility of 50 MW), compared to those in the UK of 1.5 MW (largest 3.5 MW) and in the FRG of only 0.5 MW (largest 1.01 MW) [3].

Mostly 200 until 250 kW engine units are assembled in larger facilities, which means that four 250 kW engines must be installed for the 1 MW model facility. For the engines an efficiency of about 30% and an annual operation time of 7,000 hours can be assumed. From these values a total thermal energy consumption of the model facility of $8.4x10^6$ MJ can be calculated. With the burning value of 18 MJ/m^3 about $4.6x10^6$ m^3 landfill gas per year are needed.

From the experience with landfill gas combustion engines also preliminary cost values regarding capital and O&M costs are available [8]. The capital costs depend on the performance of the engine selected and amounts to DM $4.4/W_e$ (US $\$2.6/W_e$) for a 250 kW_e engine. O&M costs vary between DM 0.08 and $0.16/kWh_e$ (US $\$0.05\text{-}0{,}09/kWh_e$), depending on the annual operation hours of the engine. For an annual operation time of 7,000 hours, the cost value derives at DM $0.09/kWh_e$ (US $\$0.05/kWh_e$). These values are very low compared to those of incinerations plants and thus landfill gas engines already can be operated economically.

4. EFFLUENTS FROM PLANTS AT DIFFERENT STAGES OF DEVELOPMENT

The evaluation of the environmental impact using waste for energy-supply, especially electricity generation, can only be done on the basis of the knowledge of the effluents to air, water and the amount of waste, which finally has to be disposed. Besides the technology of plants already existing (reference year 1990), two future periods referring to the reference years 2000 and 2020 are investigated. In contradiction to normal fossil fuelled power plants, for which sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particles are of greatest interest; for waste incineration plants the most important pollutants are hydrogen chloride (HCl), heavy metals, like cadmium (Cd) and mercury (Hg) and hydrocarbons, recently especially halogenied ones, like dioxins and furans (PCDD/F).

4.1 Waste incineration plants

The effluents from waste incineration plants can vary within a large range because of strongly varying pollutant content of different wastes and also because of different abatement efficiencies of the different abatement technologies installed. Therefore it is mainly a question of the technical regulations in different countries which values can be achieved. The implementation of the corresponding abatement technology is more a question of the costs than of the technology. In this situation already existing guidelines for admissible effluents from different countries and organizations were chosen as an orientation for the evaluation of the sets of emission factors.

(1) The effluents for the reference year 1990 are chosen from the guidelines provided in 1989 by the Council of the European Commission for waste incineration plants.

(2) The effluents for the reference year 2000 are calculated on the basis of the effluent limits of the German Technical Regulation Air of 1986.

(3) The effluent values for the reference year 2020 are calculated on the basis of the effluent limiting values of the German Technical Regulation for waste incineration plants of 1990.

In Table I, different sets of limiting values from the different regulations are compared. As all values are given as concentration values in offgas-stream, a calculation must be made transferring these values to specific energy content. For this calculation the typical offgas-amount of 5 m^3/kg waste was used [5].

The pollutants, hydrogen chloride (HCl), heavy metals, like cadmium and mercury, and specific halogenied hydrocarbons, like dioxins and furans, are the most important ones, whereas sulfur dioxide and nitrogen oxides are of minor importance. In the discussion taking place at the moment about the public acceptance of waste incineration dioxins and furans (PCDD/F) are of greatest interest. As there is a great variety of different dioxins and furans with different toxicity, a weighing system was developed referring the different single substances to the toxicity of tetra-chlorine-dibenzo-dioxin (TCDD); the resulting sum is called TCDD-equivalent (TCDD-equ.).

Table II compares three emission factor sets for the years 1990, 2000 and 2020. For all three sets of emission factors there is a need for the abatement of hydrochloride and particles. The emission factor set (1) can be achieved by the installation of a dry scrubber with removal efficiencies for HCl and SO_2 of 90 and 70% and a collection device for particles, like electrostatic precipitators (ESPs). With this abatement technology a TCDD-equ.-value in the off gas of about 1 ng/m^3 or 6 ng/kWh (e + dh) can be achieved. For the determination of the NO_x-emissions from operation experiences the value of 300 mg NO_x/ml in plant offgas was chosen and not the higher value of 500 mg NO_x/m^3 of the German Technical Regulation Air. For emission factor set (2) in most cases there will be the need for a more than 70% reduction of the SO_2-emissions. This can be achieved by a one or still better by a two stage wet scrubber facility. Furthermore a particle collection system must be installed. Much stronger demands must be achieved by the abatement system for emission factor set (3). The very low particle emission value of 60 mg/kWh (e + dh) will force a very efficient particle collection system, mostly a fabric filter system. The low values for HCl and SO_2 can only be achieved by a two stage wet scrubber. Furthermore there will be a need for a NO_x-reduction system, like a SCR-device. Great efforts have to be made for achieving the very low dioxin and furan emission value of 0.6 ng/kWh (e + dh). This extreme low value means that eventually an adsorption system on the basis of charcoal has to be installed.

Table I Effluent limiting values for waste incineration facilities from different technical regulations

Substance	Effluent limiting value mg/m^3 i.N.		
	German Techn. Reg. Air from 1986	Directive 89/369/EEC from 1989	German Techn. Reg. on Waste Incin. Facilities from 1990
Particles	30	30	10
CO	100	100	50
Organics	20**) (class I)	20	10 (total carbon)
SOx (as SO_2)	100	300	50
NOx (as NO_2)	500	no values	200
HCl	50*)	50	10
HF	2,0*)	2,0	1,0
Special anorganic particles			
class I	Cd+Hg+ Tl 0,2**)	Cd+Hg 0,2	Cd+Tl 0,1 Hg 0,1
class II	As+Co+ Ni+Se+ Te 1,0**)		
class III	Sb+Pb+ Cr+CN+ F+Cu+ Mg+Pl+ Pa+Rh+ V+Sn 5,0**)	Pb+ Cr+ Cu+ Mn 5,0	As+Co+ Ni+Cr+ Cu+Pb+ Sn+Sb+ Mn+V 1,0
Special anorganic vapors and gases			
class I	H As, ClCN, $CoCl_2$, H_3P je 1,0**)		
class II	HBr, Cl_2, HCN, HF, H_2S je 5,0**)		
Carcinogenic substances			
class I	0,1**)		
class II	1,0**)		
class III	5,0**)		
TCDD-eqv.	no values	no values	0,1ng/m^3

*) additional commitment of a percentage of pollutants in the fuel being emitted

**) additional commitment of a flue gas stream higher than a specific amount

Source: SRU, 1990

4.2 Landfill-gas facilities

The effluents of landfill-gas facilities also depend on the pollutants in the landfill-gas and on the abatement technology being installed. In the same way as is the case for incineration plants the effluents from the facilities are strongly determined by the technical regulations of the different countries. The emission factors of the facilities were therefore chosen by orientation on the following regulations.

(1) The effluents for the reference year 1990 are chosen from the values of the German Technical Regulation Air of 1986.
(2) The effluents for the reference year 2000 are calculated on the basis of the demands of the German Regulation Waste of 1990, meaning that offgas-cleaning installations must be installed.
(3) For the reference year 2020 a further improvement of the offgas-cleaning technology is supposed.

The pollutants of greatest importance regarding landfill gas combustion are, as already mentioned, the different types of hydrocarbons, like polycyclic aromatic hydrocarbons (PAH) and especially halogenied hydrocarbons, like dioxins and furans (PCDD/F).

Facilities already in operation show the following typical emission values referred to 5% offgas oxygen content [7, 9]:

Carbon dioxide (CO_2)	8.7	Vol.%
Carbon monoxide (CO)	350	mg/m^3
Sulphur dioxide (SO_2)	60	mg/m^3
Nitrogen oxides (N_2O)	4,000	mg/m^3
PAH	3.2	$\mu g/m^3$
TCDD-equ.	0.018	ng/m^3

Assuming an energy content of landfill gas of 18 MJ/m^3, an engine efficiency of 30% and further technical data of a landfill combustion engine as described in [9], specific emissions derive at:

Carbon dioxide (CO_2)	0.6×10^6	mg/kWh_e
Carbon monoxide (CO)	1,246	mg/kWh_e
Sulphur dioxide (SO_2)	214	mg/kWh_e
Nitrogen oxides (N_2O)	14,240	mg/kWh_e
sum PAH	11.4	$\mu g/kWh_e$
TCDD-equ.	0.06	ng/kWh_e

Values in Table II are chosen for the reference year 1990. While the emission of SO_2 is relatively low, compared to those from waste incineration, those of NO_x are relatively high. Catalysts for NO_x-reduction in landfill gas engines are difficult to install because of the corrosion problems caused by high chloride content of the offgas. Therefore NO_x-reduction is done by lean burning operation of the engine, which means operation with high air excess. In this operation mode a NO_x-emission of about 400 mg/m³ or 1,400 mg/kWh$_e$ can be achieved. Lean burning also reduces the CO-emissions of the engine by about 90%. The corresponding emission factors for the reference year 2000 are shown in Table II as well.

Table II Air borne emission factors of waste incineration plants in different stages of development, reference years

	1990 (set 1)	2000 (set 2)	2020 (set 3)
SO_2 (mg/kWh (e+dh))	1,700	570	280
NO_x (mg/kWh (e+dh))	1,700	1,700	680
HCl (mg/kWh (e+dh))	850	850	170
Particles (mg/kWh (e+dh))	170	170	60
TCDD-equ. (ng/kWh (e+dh))	6	6	0.6
Greenhouse gases, especially CO_2 (g/kWh (e+dh))	1,000	1,000	1,000

e+dh electricity and district heat

Further improvement of the emissions can be achieved by offgas combustion. While there is no change regarding SO_2 and NO_x emissions, a reduction of PAH and PCDD/F emissions can be achieved [7]:

PAH	0.14 µg/m³
TCDD-equ.	0.004 ng/m³.

From these values the following specific emissions can be calculated:

PAH	0.5 µg/kWh$_e$
TCDD-equ.	0.01 ng/kWh$_e$.

These values are the basis of the emission data set for the reference year 2020 in Table III.

Table III Air borne emission factors of land fill gas facilities in different stages of development, reference years

	1990 (set 1)	2000 (set 2)	2020 (set 3)
SO_2 (mg/kWh_e)	210	210	210
NO_x (mg/kWh_e)	14,200	1,400	1,400
CO (mg/kWh_e)	1,250	120	120
PAH ($\mu g/kWh_e$)	12	12	0.5
TCDD-equ. (ng/kWh_e)	0.06	0.06	0.01
Greenhouse gases, especially CO_2 (g/kWh_e)	600	600	600

5. CONCLUSIONS

A sufficient assessment of the total environmental impact from the different technologies, waste incineration and landfill gas-burning must comprise all effluents to air, water and soil and their influences to human health, natural environment and climate. This is not possible given the available data basis, besides principle methodological difficulties are still existing for such assessments. Therefore this report can only be regarded as an early step to such a comprehensive view.

Waste incineration is mainly a treatment technology for the conversion of high toxic waste to inert substances, which can be stored without long term risk. By this way also a reduction of the total waste volume to one third can be achieved. The electric current and heat generation must be regarded as a useful side effect. The already low efficiencies for current and heat generation will further decrease in the future by the demands for emission reduction and ash treatment.

The use of landfill gas must be regarded as a limited strategy for the next decade because landfilling of mixed wastes with hazardous substances will not be acceptable for the future because of the long term risk to soil and water from substances being originally in the waste or being build up by the precursors. Therefore despite relative higher emissions to water and air by waste incineration compared to landfill gas combustion incineration must be regarded as the preferential alternative.

A convincing waste management strategy minimizing long term risk should aim the avoidance and recycling of waste. A consequence of this strategy is that electricity generation from waste will not be of major importance for the future.

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SMALL HYDROPOWER FOR ELECTRICITY GENERATION

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ABSTRACT: Generation of electricity in hydropower plants is non-polluting and represents a hundred years of well proven technology based on indigenous renewable resources. Small hydroelectric plants are particularly well suited for rural electrification in both isolated and integrated grids. Although initial development costs are higher than for most other types of generation plants, operation and maintenance costs are low, and there are no fuel costs. Fluctuations in fuel prices and foreign exchange rates will therefore not affect future generation costs. Economic life time for hydro plants are longer than for other type of generation plants. Civil works amounts on average to half of the development costs, and in some developing countries parts of the mechanical equipment can be fabricated locally. Foreign exchange requirements are therefore generally not higher than for other types of generation plants. Construction of civil works offers job opportunities for local labour. Small hydros are typically of the run-of-river type with negligible environmental impacts.

1. INTRODUCTION

Small hydropower has an important role to play in electricity generation for developing countries. It is needed to meet the basic energy needs of the domestic sectors of urban and rural populations and to develop the agricultural and industrial sectors. To accelerate the supply of electricity to rural areas, a number of countries are implementing programs of rural electrification through the development of renewable energy sources, with particular stress on small hydropower. In areas where significant water resources are present, harnessing the power of water by means of small hydropower plants is one way of providing affordable energy for the development of rural areas. This paper aims to discuss the technology, the economics and the environmental aspects of small hydropower for electricity generation.

2. SMALL HYDROPOWER RESOURCES

A small hydroelectric system may be defined as one with developmental potential of 12 MW_e or less, though it should be noted that there is no universal definition for small hydropower stations.

At present there is no complete world wide data on total available small hydropower resources. This is partly due to the very large numbers of plants involved, and due to the fact that they are by their very nature small, decentralized and, in some cases, especially in the developed countries, outside the public system.

Tables I-III show the results of a survey of small hydropower projects in more than 100 countries which have small schemes either in operation, under construction or planned [1]. The definition of small hydropower used in the survey is schemes with units of 2 MW_e or below, unless otherwise specified in the notes.

Table I. The World's Small Hydropower (In operation)[1]

Country	Gross theoretical small hydro potential (GWh/yr)	Expoitable small hydro potential (GWh/yr)	In operation		
			Number of small hydro plants	Small hydro capacity (MW)	Total generation in 1989 (GWh)
	1	2	3	4	5
Argentina		38			
Australia		1,248		35	
New S Wales				14	
N Territories				0	
Queensland				3	
S Australia				0	
Tasmania	n.a.	>543	16	14	68
Victoria	13,000	250	3	3	9
W Australia				2	
Austria		3,100	1200	320	
Bangladesh			0	0	0
Belgium				14	
Belize	u/inv	u/inv	0	0	0
Bhutan			n.a.	3	8
Bolivia				55	
Brazil	n a.	4,214	157	115	500
Burma	15	u/inv	16	9	5
Burundi				12	
Cameroon				3	
Canada	9,491	3,816	288	860	3,527
Chile				11	
China	150,000	245	>74,000	9,500	
China (Taiwan)		1,490		10	
Colombia				100	
Costa Rica	n.a.	n a.	21	21	156
Cyprus		24		1	
Czechoslovakia	28,600	287	661	201	556
Denmark			n.a.	10	4
Faroe Islands			n.a.	1	n.a.
Greenland			0	0	0
Dominica	25	130	2	3	20
Dom Republic				3	
Ecuador	136	34	5	1	7
El Salvador	417	123	7	8	53
Equat Guinea				1	
Ethiopia		20,000		3	
Fiji				0	
Finland			87	100	494
France		1,976	>1,000	<800	
Gabon			n a.	n a.	n a.
Germany (FRG)		2,000	5,882	341	1,437
Greece	5,000	1,500	3	4	9
Grenada			0	0	0
Guatemala				25	
Guyana	n.a.	n a.	1	2	n.a.
Haiti	65	55	5	7	24
Honduras				1	
Hungary	586	315	29	8	26
Iceland			13	8	45
India		5,000	100	53	
Indonesia		1,400 MW	n a.	13	n.a.
Iran				n a.	
Ireland Rep		194		1	

[1] *The information provided in the tables reflects information compiled before the unification of Germany in October 1990 Therefore the names German Democratic Republic and Federal Republic of Germany have been retained*

Table I. (cont.)

	1	2	3	4	5
Israel	n.a.	n.a.	0	0	0
Italy			900	1,050	1,350
Jamaica	84	49	3	2	2
Japan			600	538	
Kenya			8,240		
Korea Rep.		127		16	
Laos				3	
Lebanon				3	
Lesotho				2	
Liberia					
Luxembourg	23	5	10	1	3
Madagascar	20,000	61	6	2	5
Malaysia			33	13	n.a.
Peninsular			25	10	
Sabah	80	55	2	1	6
Sarawak	n.a.	n.a.	8	2	n.a.
Mauritius				19	
Mexico	577	303MW	10	12	46
Morocco				6	
Mozambique				3	
Nepal			20	8	
Netherlands		100		2	
New Zealand		912		18	
Norway				119	
Pakistan				107	
Papau N Guinea				12	
Peru			50-100	50	
Philippines	n.a.	2,744	73	77	
Poland		<50MW		100	
Portugal		15,000		40	
Romania	400	280	230	145	
Rwanda				4	
Sierra Leone				2	
Solomon Is.	n.a.	16	3		
Somalia	n.a.	600	1	4	n.a.
South Africa			0	0	0
Transkei			n.a.	3	n.a.
Spain			959	337	791
Sri Lanka		263		9	
Swaziland	n.a.	15	4	3	9
Sweden	3,600	2,000	1,000	300	1,300
Switzerland	n.a.	n.a.	880	192	913
Tanzania				4	
Thailand			45	9	
Togo				4	
Tunisia	40	20	3	3	15
Turkey				12	
UK		400		n.a.	
England				3	
N Ireland				n.a.	
Wales				n.a.	
Scotland				33	
USA				701	
USSR		493,000		400	
Vanuatu			0	0	0
Venezuela				1	
Western Samoa			6	8	
Yugoslavia				119	
Zaire				2	
Zambia		9		1	2
Zimbabwe		u/inv	6		n.a.

Table II. The World's Small Hydropower (Under Construction)

Country	Under construction		
	Number of small hydro plants	Small hydro capacity (MW)	Probable average annual generation (GWh/yr)
	6	7	8
Argentina		1	
Australia	0	0	0
New S Wales	0	0	0
N Territories	0	0	0
Queensland	0	0	0
S Australia	0	0	0
Tasmania	0	0	0
Victoria	0	0	0
W Australia	0	0	0
Austria		n.a.	
Bangladesh	n.a.	n.a.	n.a.
Belgium		3	
Belize	0	0	0
Bhutan			
Bolivia	0	0	0
Brazil	1	1	4
Burma	6	2	2
Burundi			
Cameroon		19	
Canada	0	0	0
Chile		n.a.	
China		n.a.	
China (Taiwan)	0	0	0
Colombia	0	0	0
Costa Rica	2	1	4
Cyprus		0	
Czechoslovakia	2		34
Denmark		n.a.	
Faroe Islands	0	0	0
Greenland	0	0	0
Dominica	2	5	33
Dom. Republic		5	
Ecuador	7	3	30
El Salvador	0	0	0
Equat. Guinea		n.a.	
Ethiopia		67	6
Fiji		1	
Finland	2	2	9
France		0	
Gabon	n.a.	4	12
Germany (FRG)	n.a.	n.a.	n.a.
Greece	0	0	0
Grenada		3	
Guatemala	0	0	0
Guyana	1		
Haiti	2	1	5
Honduras	0	0	0
Hungary	0	0	0
Iceland	0	0	0
India		79	
Indonesia	10	8	n.a.

Table II. (cont.)

	6	7	8
Iran		4	
Ireland Rep.			
Israel	0	0	0
Italy	n.a.	3	n.a.
Jamaica	0	0	0
Japan	11	7	
Kenya		0	
Korea Rep.		10	n.a.
Laos		n.a.	
Lebanon		n.a.	
Lesotho			
Liberia		n.a.	
Luxembourg	0	0	0
Madagascar	2		1
Malaysia	14	9	41
Peninsular	95	5	14
Sabah	4	4	26
Sarawak	1		1
Mauritius	0	0	0
Mexico	0	0	0
Morocco			
Mozambique		0	
Nepal		3	
Netherlands	0	0	0
New Zealand	0	0	0
Norway		4	
Pakistan		52	
Papua N Guinea		6	
Peru		10	
Philippines			
Poland		n.a.	
Portugal	0	0	0
Romania	79	65	184
Rwanda		n.a.	
Sierra Leone		n.a.	
Solomon Is.	0	0	0
Somalia	0	0	0
South Africa	0	0	0
Transkei			
Spain	n.a.	n.a.	n.a.
Sri Lanka		0	
Swaziland	0	0	0
Sweden	n.a.	20	290
Switzerland	5	5	19
Tanzania		1	
Thailand	0	0	0
Togo	n.a.		
Tunisia	0	0	0
Turkey		n.a.	
UK	0	0	0
England	0	0	0
N Ireland	0	0	0
Wales	0	0	0
Scotland	0	0	0
USA		49	
USSR		n.a.	
Vanuatu	0	0	0
Venezuela		1	
W Samoa		4	
Yugoslavia		n.a.	
Zaire		n.a.	
Zambia	0	0	0
Zimbabwe	0	0	0

Table III. The World's Small Hydropower (Planned)

Country	Footnote	Planned		
		Number of small hydro plants	Small hydro capacity (MW)	Probable average annual generation (GWh/yr)
	9	10	11	12
Argentina	1		76	
Australia	2			
New S Wales			0	
N Territories			0	
Queensland			0	
S Australia			0	
Tasmania	3	n.a.	n.a.	n.a.
Victoria	4	12	16	30-60
W Australia			0	
Austria	5		200	
Bangladesh	6	12	n.a.	n.a.
Belgium			n.a.	
Belize		1	7	n.a.
Bhutan				
Bolivia			10	
Brazil		7	7	31
Burma		15	8	7
Burundi			n.a.	
Cameroon			n.a.	
Canada	7	1	1	4
Chile			n.a.	
China	8		n.a.	
China (Taiwan)	9			
Colombia			35	
Costa Rica		2	2	111
Cyprus	10		1	
Czechoslovakia		11	35	115
Denmark			n.a.	
Faroe Islands		n.a.	n.a.	n.a.
Greenland				
Dominica		1	1	7
Dom. Republic			n.a.	
Ecuador		17	11	98
El Salvador		1	2	12
Equat. Guinea			n.a.	
Ethiopia	11		n.a.	
Fiji			1	
Finland		7	15	69
France	12		0	
Gabon		n.a.	2	2
Germany (FRG)	13	n.a.	n.a.	n.a.
Greece		4	4	15
Grenada		0	0	0
Guatemala			8	
Guyana		2	1	5
Haiti		3	2	11
Honduras		0	0	0
Hungary	14	1	1	5
Iceland	15	0	0	0
India			n.a.	
Indonesia	16			

Table III. (cont.)

	9	10	11	12
Iran			n.a.	
Ireland Rep.			3	
Israel		1	3	n.a.
Italy	17	n.a.	10	n.a.
Jamaica		2	1	6
Japan				
Kenya			n.a.	
Korea Rep.	18		n.a.	
Laos	19		197	
Lebanon	20		n.a.	
Lesotho			n.a.	
Liberia			n.a.	
Luxembourg	21	0	0	0
Madagascar	22	1		1
Malaysia	23	15	9	42
Peninsular		3		
Sabah		7	2	13
Sarawak		5	7	29
Mauritius		0	0	0
Mexico	24	263	121	531
Morocco			20	
Mozambique			1	
Nepal		10	2	
Netherlands	25	n.a.	n.a.	n.a.
New Zealand	26			
Norway	27		13	
Pakistan			105	
Papua N Guinea			n.a.	
Peru			25	
Philippines		95	131	
Poland	28		n.a.	
Portugal	29	0	0	0
Romania		218	150	413
Rwanda			n.a.	
Sierra Leone			n.a.	
Solomon Is.		4		2
Somalia		u/inv	u/inv	u/inv
South Africa		0	0	0
Transkei				
Spain		u/inv	u/inv	u/inv
Sri Lanka	30			
Swaziland		1		2
Sweden	31	n.a.	20	200
Switzerland	32		n.a.	2
Tanzania			1	
Thailand				
Togo			n.a.	
Tunisia		4	2	15
Turkey			n.a.	
UK	33	0	0	0
England		0	0	0
N Ireland		0	0	0
Wales		0	0	0
Scotland		0	0	
USA			n.a.	
USSR	34		3,200	
Vauatu		1		n.a.
Venezuela			2	
W Samoa		0	0	0
Yugoslavia			n.a.	
Zaire			n.a.	
Zambia	35	n.a.		0
Zimbabwe		0	0	0

Notes:

1. *Argentina: exploitable potential figure is for schemes < 1 MWe.*
2. *Australia (total): exploitable potential figure is for schemes 100 kWe - 15 MWe.*
3. *Australia (Tasmania): 36 potential sites have been identified, with a total capacity of 62 MWe.*

Table III. (cont.)

4. *Australia (Victoria): exploitable potential figure is for schemes which are technically feasible, but not necessarily economic; planned figures relate to results of a feasibility study.*
5. *Austria: exploitable potential figure is for schemes < MWe.*
6. *Bangladesh: 12 sites have been proposed for feasibility studies.*
7. *Canada: the data in the table is for schemes of 10 MWe or less. The capacity in operation for schemes of 2 MWe and below is < 50 MWe.*
8. *China: gross potential figure given is in kW; exploitable potential figure given is for schemes < 25 MWe. There is 3,693 MWe capacity in operation of schemes < 500 kWe, with a probable annual generation of 6529 GWh/year. The number of schemes given in the table and their capacity are for 1984.*
9. *China (Taiwan): exploitable potential figure is for schemes < 1 based on a preliminary study.*
10. *Cyprus: exploitable potential figure is for schemes < 1 MWe, based on preliminary study.*
11. *Ethiopia: all data relate to schemes < 1 MWe.*
12. *France: exploitable potential figure is for scheme < 1 MWe. Almost all small hydro is owned by individual producers.*
13. *Germany (Fed. Rep.): all data relate to schemes < 1 MWe. The capacity in operation for schemes with units of 2 MWe or below is 416 MWe.*
14. *Hungary: in addition to the planned scheme shown, it is planned to reconstruct 14 existing plants.*
15. *Iceland: in addition to the 13 plants shown which are in the public sector, there are 192 privately owned plants with a total capacity of 3,771 MWe*
16. *Indonesia: data are for 1986; there are a further 291 potential sites with a total capacity of 1,340 MWe.*
17. *Italy: data are for plants of 1.5 - 10 GWh/year capability; an ENEL study has identified 700 potential plants, of total capability 2500 GWh/year.*
18. *Korea (Rep. of): exploitable potential figure is for schemes < 1 MWe.*
19. *Laos: the in operation figure is for schemes < 1 MWe.*
20. *Lebanon: the in operation figure is for schemes < 1 MWe.*
21. *Luxembourg: exploitable potential figure is for schemes < 1 MWe.*
22. *Madagascar: data are only for JIRAMA (power board) plants.*
23. *Malaysia: 82 potential sites have been studied; 22 pilot schemes have been completed since 1980.*
24. *Mexico: exploitable potential figure is in MW.*
25. *Netherlands: exploitable potential figure is for schemes < 1 MWe; there are also several private plants of capacity 30 - 50 kWe.*
26. *New Zealand: exploitable potential figure is for schemes < 1 MWe*
27. *Norway: data are for plants 1-2 MWe; there are an estimated 500 plants < 1 MWe each, with a total capacity of about 200 MWe.*
28. *Poland: exploitable potential is less than 50 MWe.*
29. *Portugal: exploitable potential is for schemes < 1 MWe.*
30. *Sri Lanka: exploitable potential is for schemes < MWe; 140 potential sites have been identified, with a total capacity of 95 MWe.*
31. *Sweden: data are for schemes 1 5 MWe*
32. *Switzerland: annual average generation of small hydro in operation is given; under construction figures are for schemes of 300 kWe - 2 MWe capacity.*
33. *UK: exploitable potential figure is for schemes < 1 MWe*
34. *USSR: exploitable potential figure is for schemes < 1 MWe*
35. *Zambia: all data are for schemes < 1 MWe.*

3. SMALL HYDROPOWER TECHNOLOGY

Small hydro is not a new concept. It is an old but reliable energy source which technology had already been developed and put into use since the last part of the 19th century and in the early part of this century, to provide power for towns and isolated mines and industries. Although some of these plants are still functioning successfully, many of them were abandoned during the time when petroleum fuel was inexpensive. However, the existence of these old plants proves that the technology is well-proven, well beyond the research and development stage.

Aside from being a well known and tested technology, the equipment used is relatively simple and as a result of this, major components can be manufactured by a number of developing countries. It utilizes a continually renewable, indigenous resource and is non-polluting compared to other conventional source of energy. The project can also be, and is often a part of a water development scheme such as a water supply and irrigation system to maximize the benefits and also reduce the cost of the project. The civil works construction costs can be reduced by simple design and using local resources. A small hydro plant has a very low operating cost, a long service life of 30-75 years and is relatively cheap and simple to maintain. These characteristics of the small hydro technology are of major advantage to a developing country environment.

A small hydropower plant is an installation where hydraulic power is used to generate electricity by means of one or more turbine generators. Figure 1 illustrates typical lay-outs of small hydro systems. The basic components of a system normally include a dam or weir, intake structures, desilting basin, headrace, forebay, surge tank, penstock, the electro-mechanical equipment and the powerhouse.

3.1 Dam

A dam is a structure built across the watercourse to increase the available head, to provide storage or to divert the flow of water. When the site has a flat terrain, a dam may be constructed to increase the head, so that the required power can be generated from the available flow. A dam is also constructed to provide a reservoir to store water in sites where the flow is insufficient to meet the power demand with the available head. In certain sites where there is sufficient head and flow, there is no need for a dam. These schemes are called run-of-river schemes where a portion of the flow in the stream is diverted towards the powerhouse. A low diversion structure or weir is constructed across a portion or all of the stream to divert the required water into the intake.

The design and construction of a dam requires technical expertise. Incorporating a dam that is not essential in the system make the project costly, longer to build and can add additional maintenance problems. When a dam is considered advisable in a scheme and it is omitted, there may result inadequate potential to meet present or future power demands.

Dams for small hydro power plants may be constructed using concrete, timber or earth materials. The kind of materials used will depend on the design and availability.

3.2 Intake structure

The intake is the structure that permits a controlled flow of water from the river or stream into the conduit which eventually carries the water to the turbine to generate power. A function of the intake is to minimize the amount of debris and sediment carried by the incoming water from entering the conduit.

3.3 Headrace

The headrace is used to convey the water from the intake to the forebay a relatively long distance with minimum loss of head. The conduit may either be an open channel or closed conduit which may either be a pressurized or non-pressurized or a tunnel. A headrace conduit can be made of welded steel, ductile cast iron or glass reinforced pipes. For very small and simple systems, the conduit maybe just a canal excavated in soil lined with concrete or stone-concrete masonry, half-round wood or sheet metal. The type of headrace to be used would depend on the topography of the site.

3.4 Forebay

The forebay is a structure located at the end of the headrace which serves as a small intake reservoir to the penstock. The forebay may also serve as a final settling area for debris which has passed through the intake or swept into the canal, before the water passes through the turbine. It can also serve as a reservoir to supply water to the turbine for a longer period. A spillway might be incorporated to remove excess water.

3.5 Surge tank

A surge tank is a structure whose function is to provide a free reservoir surface as close to the turbine as possible to absorb and compensate effects of water hammer. It also dampens water level fluctuations due to load changes on the systems. Sometimes a surge tank is used instead of a forebay.

3.6 Penstock

The penstock is a pressurized conduit that conveys the water from the forebay or the surge tank to the turbine. Penstocks are commonly made of steel, ductile cast iron, glassfibre reinforced pipes, concrete or wood. The choice of materials will depend on the pressure head and discharge to be handled and the cost of the material and its installation. The wood can be used for low pressure head. The massive reinforcement required makes concrete penstocks at high head very expensive. The penstock may be exposed or above ground depending on foundation conditions.

3.7 Powerhouse

The powerhouse houses the electro-mechanical equipment. The size of the powerhouse can range from a very simple structure covering the turbine, the generator and control equipment to one which may include a maintenance or erection area, a service area, an office and sometimes quarters for the operators. The floor area varies depending on the type of turbine and generator, number of units and general arrangement in the powerhouse as adapted by the different countries.

3.8 Turbine

Turbines are hydraulic motors that convert the water energy into mechanical energy. The type and capacity of turbine for use at a particular site depend on the rate of flow and net available head.

There are two general classifications of hydraulic turbines, impulse and reaction. Impulse turbines have a case full of air in which a jet of water is directed into a runner, while reaction turbines run completely full of water. Impulse turbines are Pelton, Turgo impulse, and cross flow. Reaction turbines are further divided into Francis (mixed flow) and propeller type (axial type).

3.9 Alternating current generators

Coupled to the turbines are the alternating current generators which generate electric power from the mechanical power imparted to the turbines by the cascading water. The generator capacities are dependent on stream flow and the head of water of the selected site. The power station should be able to operate during periods of minimum flow and also should be able to utilize the power available during maximum flow periods. Multiplicity of units of the same size is resorted to fulfill this requirement.

Also part of the power station complex is a substation through which the power delivered from the generators is transformed to a higher voltage before delivery to the outgoing lines. This function is done by a power transformer mounted inside the substations.

4. ECONOMIC ASPECTS IN SMALL HYDROPOWER DEVELOPMENT

A comparative analysis of the cost of supplying energy from an alternative source is required to establish the value of a hydropower project. Most often the comparison is with a thermal or hydroelectric plant connected to a grid or in the case of isolated systems the comparison is with a small diesel generator. In the analysis of which energy alternative is the most cost effective, several factors are taken into consideration like the cost and availability of diesel fuel, the unit installed cost of the alternative energy source and replacement cost, cost of extending the power lines from the grid to the site and whether the energy demand can be met by the project considering that for renewable energy systems the energy supply patterns may be intermittent. For project to small isolated communities, it is important to consider the social acceptability and ease of operation and maintenance of the system.

Experience has shown that the cost per kilowatt installed of small hydropower projects varies, depending on site-specific factors. Three factors which influence costs are: available head, water supply and accessibility of site. Projects with high heads are cheaper because they enable energy to be generated with less water than low heads, therefore the equipment used can be smaller and less complex. The quality of water supply should be free of sediment which could damage the plant, and should be available all year round. Poor quality of water would require structures to remove the sediments and other foreign substances from the water, thus increasing costs. Intermittent water supply may require incorporation of dams for storage during low-flow periods. The access road would be expensive for sites with difficult terrain.

Investment costs include planning and design, materials, labor, equipment, construction period interest, and contingency costs. A number of developing countries are able to build plants at very low costs on the basis of local initiatives. Some of the methods used to reduce costs are:

- Building up local capability in the planning and design of projects.
- Making use of standardized designs, improvising civil works components, using locally available materials at the site.
- Using local labor force and labor intensive methods of construction.
- Fabricating turbines and accessories locally using simple construction techniques.

Although the above methods may result in plants that do not make use of the full energy potential of sites, the energy requirements are likely to be modest in remote rural areas.

The plants may not be very efficient and would need frequent maintenance and earlier replacement, but they will be easier to maintain and replace than conventionally engineered plants.

The operation and maintenance (O&M) costs for small hydropower are very low, generally considered to be 1.5% of capital costs. The normal maintenance for small projects would be cleaning of the dam site and removing leaves and debris from the trash racks and open canals. Many small hydro plants are unmanned.

The indirect costs include environmental costs, such as resettlement of displaced population in case a big reservoir is needed.

Small hydro projects are site specific, which makes it difficult to make an accurate breakdown of costs. A breakdown of costs with maximum and minimum civil works costs is shown in Fig. 2.

Capital costs are meaningless in the determination of unit energy costs unless the degree to which the plant is utilized (plant factor) is taken into account. Unit energy costs depend on capital costs, operation and maintenance and capacity utilization.

An economic cost analysis of a small hydro plant is as shown in Table IV.

Table IV. Economic Costs Ananlysis

Capacity	5 MW_e
Plant Factor	60%
Generation	26 GWh/yr
Construction cost % elec-mech	2,000 US$/kW 50%
Economic life time civil elec-mech	 50 years 25 years
Construction period	2 years
Disbursement/year	50%
Operation and Maintenance (1.5% per year)	150,000 US$/yr
Discount rate	12%/yr
Generation costs	0.056 US$/kWh

The capacity utilization of a plant is affected by the water supply conditions. In certain regions, particularly in the tropics, the concentration of annual rainfall during wet seasons frequently causes intermittent flows in small rivers and streams. In areas like this, unless the system has a dam to store the excess flow during the wet season, the plant's operation may be limited during the dry season. In most countries, it is a practice to install multiple units in a power station. The plant is designed such that during the dry season at least one unit can still run. In this case, the power plant can operate all year round.

Another factor that may constrain plant utilization is irregularities in demand. The ratio of the average load to the peak load or load factor, indicate the nature of demand constraints for a given plant. Low load factors indicate that plant use is high only for very short periods, and power consumption is very low during other times. The load factor is important for small hydro stations, and low load factors can have disastrous effects on the economic viability of the plant. After the plant has been built, there should be efforts to promote the use of electricity.

In the evaluation of small hydro plants, decision-makers have a tendency to utilize criteria and cost/benefit analysis as if they were evaluating a major hydropower project. The decision makers should be prepared to take into consideration the social and economic impact the project will have upon the community. The evaluation should include an analysis of the future benefits the project will bring to the community, in terms of alternative economic growth.

5. ENVIRONMENTAL ASPECTS OF SMALL HYDROPOWER PLANTS

Small scale hydropower is considered to be an environmental clean technology relative to non-renewable technologies. It has the advantage of using no fuel and generating no process residuals such as waste heat, air emissions, solids, waste and toxic substances.

The most serious environmental site development impacts are associated with the construction of a dam for storage. The significant overall effect is the permanent change of aquatic habitat from flowing streams to a reservoir and the flooding of the terrestrial habitat associated with the stream. This results in changed ecosystems: aquatic insects, invertebrates, plants, algae and fish change from those associated with a cool, swift running stream to those which thrive in a relatively warm, still lake environment. The dam also serves as a block for species migrating up and downstream.

There are other dam related potential impacts. Evaporation, seepage and dam safety are some of the issues that should be addressed in planning. There will be an increase in loss of water through the increased surface of a reservoir, particularly in zone of high solar incidence.

A dam can also significantly increase the incidence of certain diseases by providing breeding grounds for disease- carrying organisms, particularly in the tropics. Malaria and schistosomiasis are example of such diseases. A dam might also effect the fish which might be a source of both food and income for the population by decreasing streamflow, reducing levels of dissolved oxygen, or changing water temperature.

The impacts from the construction of facilities for run-of-river schemes are similar to those of dams but with less intensity and most importantly, no impoundment. For diversion projects, an environmental impact will be the effect of the stream diversion, which will wholly or partially dry up the former stream bed between the diversion and the powerhouse. This will primarily affect aquatic life.

Other construction impacts derive from the development of the access road is noise and dust during construction. The general effect of kind of activities is to frighten away wildlife, which may or may not return, depending on the degree of habitat disturbance.

The most significant water resource impact of construction is the introduction of sediment into a stream. Suspended sediments cause turbidity, which, in addition to being aesthetically displeasing, can reduce light penetration and primary productivity. Sedimentation can also introduce nutrients, organic matter, and some toxic substances such as pesticide into receiving waters, depending on the source.

Several construction practices should be employed as needed to reduce sediment release. These include: mulching and seeding of slopes, using stone and riprap for channels and embankments, and construction of settling basins for discharge of highly turbid water.

Operations of turbines particularly at dams, can cause adverse impacts to organisms passing through the turbines, especially fish which are migrating downstream. Fish bypass systems may be used to mitigate impacts to migrating fish, but economics could constrain the use of these systems. Agriculture and forestry may be affected through mundation.

Small hydropower has also positive impacts. It is considered an environmentally clean technology compared to non- renewable technologies. It uses a renewable resource and generating no process residuals. It is an appropriate technology for developing countries. The principal environmental advantage is the relatively small size of the project, and the relatively small scale of any attendant impacts from construction and operation. In systems where there is an impoundment, the reservoir can be developed into recreational facilities. Hydropower development may be complementary to irrigation and water supply. It can provide power for these systems and capital costs are reduced in this case of multi-purpose utilization of water resources.

6. OUTLOOK FOR SMALL HYDROPOWER DEVELOPMENT

Small hydropower is a useful source of electricity supply in decentralized rural areas. Extension of the centralized grid is usually uneconomical, considering the high investment cost and low initial power demand. Development of small hydro in these areas will enhance development and uplift the quality of life of the local population, contributes to modernization of forming and promotes socio-economic and industrial progress.

Small hydropower technology is relatively simple and well known by a growing number of developing countries. It is considered to be an environmentally clean technology compared with conventional energy sources. It uses renewable, fuel less resources and generates no process residuals. Saving of the fossil fuel and alleviation of dependence on foreign energy suppliers is an important advantage in favor of small hydro.

One of the constraints in the development of small hydro is a high capital cost per kW of installed capacity. Investment costs may be reduced by using simple designs and local resources. Small hydropower can be and is often a part of a multi-purpose development of water resources such as water supply and irrigation projects. Other important advantages of small hydropower are low operating cost, long service life and they are relatively cheap and simple to maintain.

Considering the above mentioned advantages, small hydropower, whenever the energy resource exists, can be a viable alternative in providing electricity to areas where previously unavailable, thereby improving living conditions, opening doors for new economic opportunities and alleviating the burden of purchasing commercial energy.

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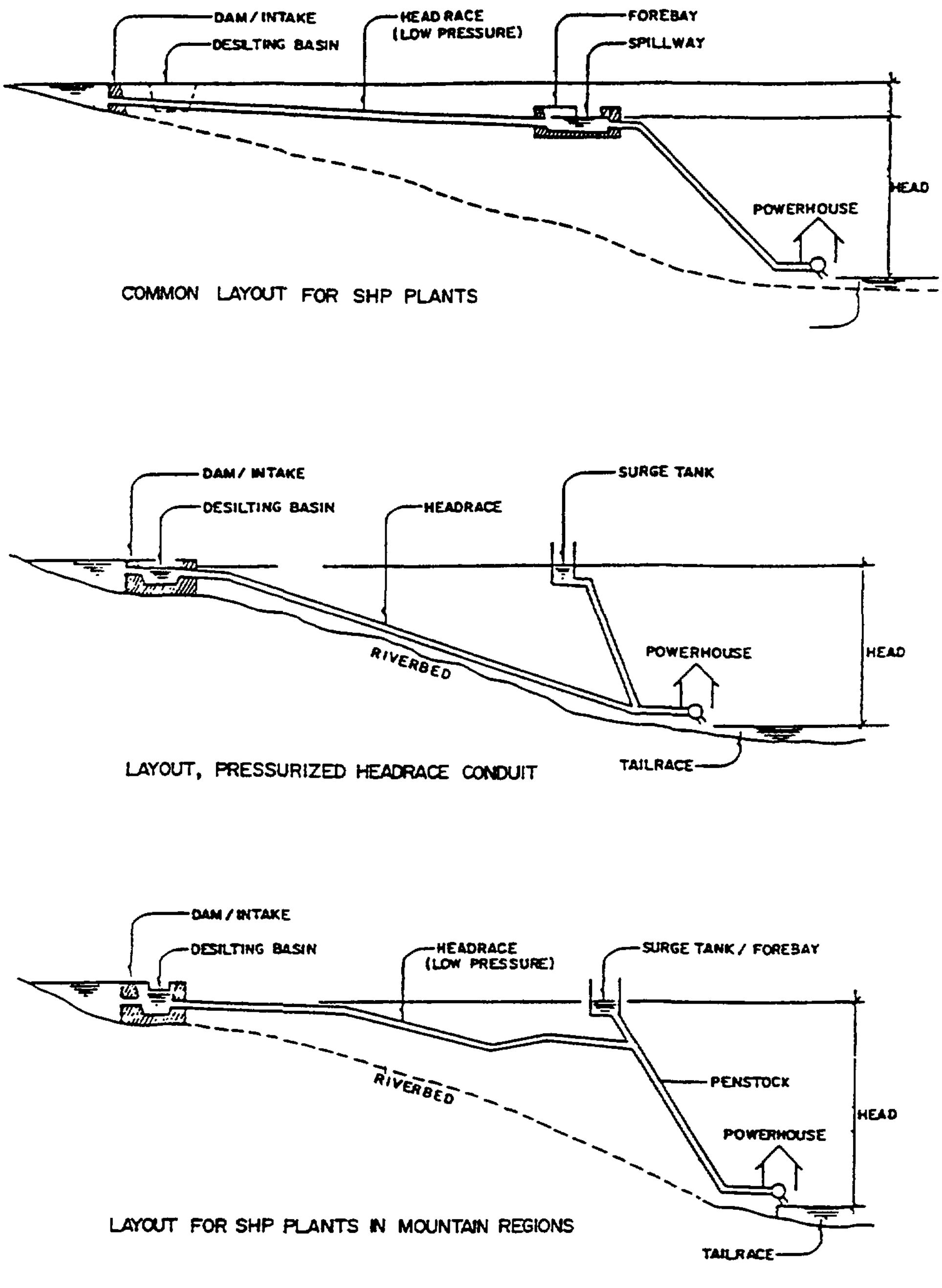

Fig. 1 Alternative Layouts for Small Hydropower Plants.

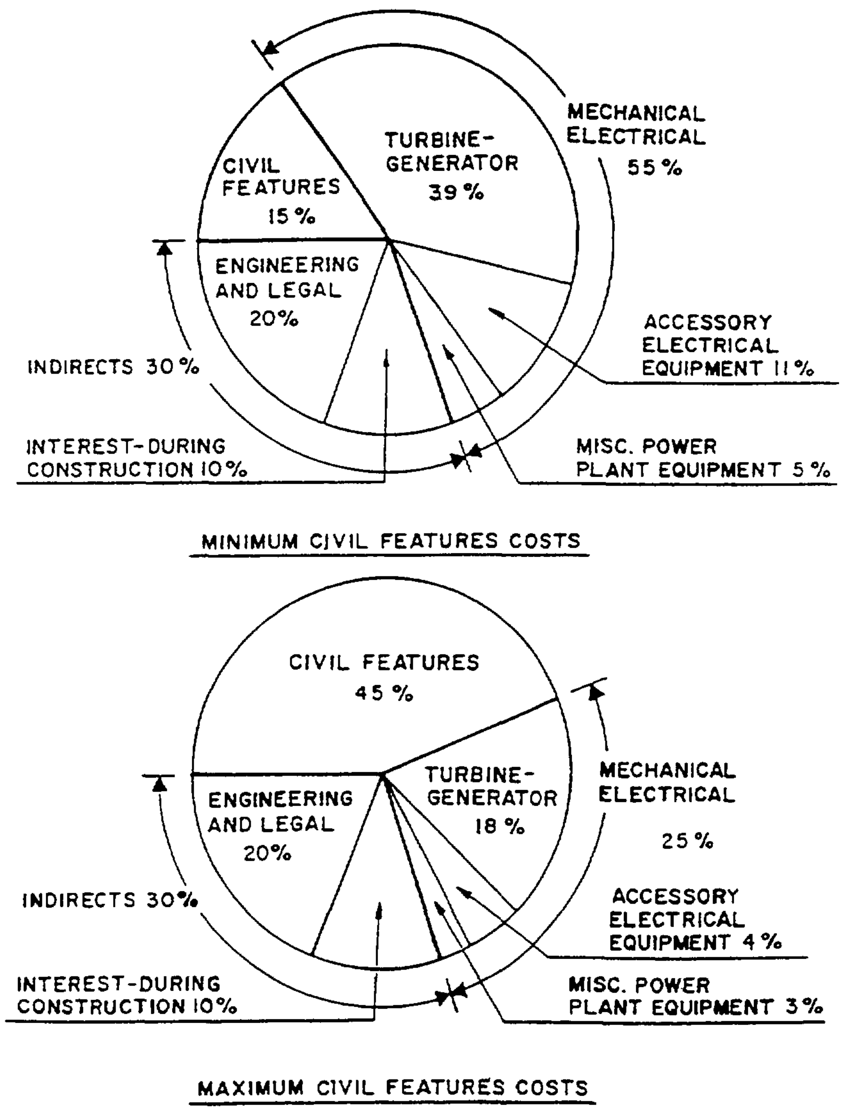

Fig. 2 Cost Components of Small Hydroprojects.

NUCLEAR TECHNOLOGY

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ABSTRACT: Nuclear power currently provides about 17% of the world's electricity (20% in OECD countries). This paper briefly presents the basic technology of nuclear power and its fuel cycle. It notes the types and control of emissions from normal operations and the techniques and regulations adopted to promote safe operation. It provides an overview of the fuel resources and the current contribution to electricity production and hence its displacement of other types of pollution. It reviews the expectations of future development of nuclear power and its economics.

1. THE NUCLEAR REACTOR

A typical nuclear reactor consists of a specially engineered container (most commonly a steel pressure vessel) which holds an array of uranium fuel elements. If conditions are right, the close proximity of the uranium fuel elements with one another creates a heat producing reaction at the atomic level called 'fissioning'. The heat is transferred from the hot fuel elements to a cooling fluid (usually ordinary water) which in turn is used later on to produce steam to drive a turbine and generate electricity.

Some heavy atoms, such as certain forms or isotopes of uranium, can absorb a neutron particle which causes the heavy atom to split apart or 'fission' into smaller pieces. A loss of mass occurs during this fissioning process, with the loss of mass appearing as released energy. The amount of energy released is enormous when compared with chemical reactions, such as coal burning which were previously used in electricity generation – almost a factor of a million more! This explains the considerable excitement over the potential for the fissioning process to become a vast source of energy for the future. After all, the energy available in one gram of uranium was found to be equivalent to that in 2.5 tonnes of coal. Large research efforts were begun in many countries to explore this potential energy source with most work focusing on the fissioning of a particular atom – the isotope Uranium 235. This isotope was found to fission most easily, but only occurs as about 0.7% of natural uranium. Thus efforts to develop an enrichment process were begun as well. The more prevalent isotope, ^{238}U, with three more neutrons in its nucleus was also found to fission but not as easily. ^{238}U can, however, capture a neutron, and decay into other elements (such as Plutonium) which are more readily fissionable. Thus ^{238}U is an important indirect source material for the fissioning process.

The key to releasing fission energy successfully on a commercial scale depends on the ability of the reactor designer to provide a self-sustaining reaction and suitably control it.

Whether or not there will be a self sustaining reaction (i.e. whether the core will go 'critical') depends on many factors such as the concentration of 'fertile' isotopes such as ^{238}U, the concentration of fissile isotopes (e.g. ^{235}U), the concentration of elements which will absorb the neutrons without any further reaction, and the energy of the neutrons themselves, which can affect the probability of the neutron being captured or causing an energy release when it is captured. The core of a nuclear reactor is designed and operated so that the chain reaction proceeds in a controllable manner to give the required amount of energy. There is no possibility whatever of a nuclear explosion of the kind achieved in nuclear weapons.

The neutrons emitted from a fission are highly energetic and, in reactors designed to convert uranium into energy, need to be slowed down in order to increase the chances of a capture yielding useful energy. This is achieved by surrounding the fuel elements with a material, called the moderator, which will do the slowing down without capturing neutrons. Carbon in the form of graphite, heavy water and normal water have been used for this purpose. In the last case there is a need to enrich the fuel in ^{235}U to provide more favourable neutron economics and to compensate for uneventful absorptions.

2. CONTROL

In order to control the rate of the reaction either to start up or shut down, a number of control rods is inserted into the core. These rods contain material which absorbs neutrons.

If the reactor has to be shut down they are inserted fully, either automatically or under operator control. Control during normal operations to maintain the required temperatures can be exerted by introducing a neutron absorber, such as boron, into the moderator at a desired concentration. In designing reactors, advantage is taken of the reduction of reactivity which takes place when the fuel gets hot and (in boiling water reactors) when local bubbling of the water creates a void and the neutrons are insufficiently moderated.

3. SAFETY

The aim of operating the reactor is to produce heat that can be turned into electricity but that has to be subject always to ensuring that the risk of an accident is kept as small as possible and within the nationally applied regulatory limits. To achieve this the fuel must be kept below a defined temperature and all the barriers which prevent egress of radioactive products must be kept intact. A strategy known as 'defence in depth' has been adopted whereby a combination of at least two unlikely events has to occur before the cooling of the fuel can fail or the escape of radioactivity can take place. Examples of this are the placing of the fuel inside a gas-tight can, inside the pressure vessel of a Pressurized Water Reactor, inside a pressure tight containment building; and the multiple systems to ensure cooling of the core during an emergency. Much redundancy of components such as water injection pumps and of pathways for feeding in back-up electrical power is also provided.

In all countries where nuclear plants are operated there is an elaborate scheme of national control whereby regulations set the safety goals. The national authorities accept that provided these goals are met there will be no unacceptable risk to the public. At various stages prior to and during construction and during operation an independent team of inspectors has to be satisfied that the regulations are met. In some countries plant operators are required to perform periodical inspection and maintenance.

Safety concerns have come to dominate much discussion about the nuclear industry. The Three Mile Island (TMI) and especially Chernobyl accidents have caused a severe setback to the nuclear industry. The TMI event was a severe economic disaster but caused no deaths and no injuries. Official statistics from the Union of Soviet Socialist Republics [1] indicate that the Chernobyl accident killed 31 persons, while a large area of land was contaminated leading to large economic losses.

The impact of Chernobyl was strong because safety was expected to be near-perfect in the nuclear industry which was approaching 50 years old and had had few major problems preceding the two accidents just mentioned. Serious industrial accidents of all types appear to be increasing in frequency with 12 accidents having caused more than 100 deaths each since 1974 [2]. By far the worst in terms of mortalities was the Bhopal accident (2,800 deaths). It was estimated [3] that in 1975 coal use in electricity production has killed 1,900 to 15,000 persons and oil between 88 and 4,400. The relative success of the nuclear industry in meeting safety goals is illustrated by a US study published in 1987 [4] in which the fatalities (workers and public included) associated with the whole fuel cycles of various fuels were compared. It was calculated that the ratio of these fatalities per unit of electricity output when using coal, oil, natural gas or uranium in LWRs was 13:10:0.2:0.4. Nevertheless, no one, the nuclear industry included, is prepared to countenance another accident approaching anywhere near the scale of Chernobyl, so there is a continued effort to improve safety performance at all nuclear facilities.

4. FUEL CYCLE

A distinguishing feature of the use of nuclear power is that, from the earliest days of its exploitation, attention has been given to the safety, reliability and economy of the whole fuel cycle. This starts with the extraction of uranium-bearing rock and proceeds to the final disposal of all the waste products, in particular those which are radioactive.

Uranium is very wide spread throughout the earth's crust and in seawater but its occurrence in economically mineable deposits is limited. The currently acknowledged resources in market-economy countries, that are extractable at up to $130/kg U, are put at some 2.2 million tonnes. These resources are well delineated. Additionally estimated resources, and those speculated to exist, take up the amount in these countries to some 16 to 18 million tonnes [5].

Production of uranium in this group of countries is running at around 30,000 tonnes U annually. This is to be compared with an annual demand of about 43,000 tonnes U and an inventory of around 140,000 tonnes U, all figures relating to 1989. Several methods of production are in use including deep underground mining, opencast mining and in situ leaching of uranium from its host rock.

The first two methods give rise to releases of radioactive radon which, if not properly controlled, can be a health hazard to miners. They also produce large quantities of mine tailings which may need special engineering to avoid contamination of water resources with heavy metals and radioactivity. Uranium is also recovered as a by-product in the production of gold or phosphates.

Some uranium ore in Canada contains more than 10% of uranium [6] but the level is more usually 1% or less. Various concentration processes are in use yielding a 'yellow cake' of uranium oxide (U_3O_8). This commodity can be refined further to produce the metal fuel which is used in French and British gas cooled reactors. More frequently nowadays it is converted into uranium hexafluoride which is a gas at normal temperature and pressure. This material is a convenient feedstock for enrichment plants. These use the small difference in atomic weight between ^{235}U and ^{238}U to concentrate ^{235}U either by a diffusion process (United States of America and France) or by a centrifuge process (Federal Republic of Germany, Japan, Netherlands, the USSR and the United Kingdom). The enriched hexafluoride is then converted back to uranium oxide (UO_2) and sintered into pellets for fabrication into fuel elements.

The pellets are sealed in a gas-tight tube or cladding made of a corrosion resistant material. An alloy of magnesium was used in the early gas cooled reactors; various forms of stainless steel and zirconium alloy have been used in other reactor types. These tubes are then bundled into a fuel assembly that can conveniently and reliably be placed into the core. As for all component manufacture in the nuclear industry, much effort is expended in metallurgical and other quality control. Documentation of all tests is prepared which enables very thorough checking back in case of any malfunction.

Reactor fuel stays in the core for about three years. It is then removed using a machine which protects workers from the radiation and is set aside (usually in a pond under water) to cool, in terms of radioactivity. The fuel from Magnox reactors needs to be processed after a few years as it corrodes. Other fuel types can be left for decades under water. It sometimes becomes economic to consolidate the spent fuel elements into smaller containers thus reducing the need to invest in spent fuel storage capacity. Eventually decisions will be taken as to whether to dispose of the spent fuel without removing the fuel from the cans or to take out the fuel pellets and chemically reprocess them to recover plutonium and the as yet unused ^{235}U, which may still be at a higher concentration than occurs naturally. The value of these recovered metals can have a noticeable effect on the relative economics of the two approaches.

The preferred final solution in either case is to place the highly radioactive waste (HLW) in deep, geologically isolated repositories in which a number of engineered barriers as well as the natural properties of the host rock are used to prevent the escape of radioactivity. Direct disposal of spent fuel creates a higher need for the most expensive forms of storage space as the highly radioactive component of the waste from reprocessing can be concentrated into a glass or an artificial rock of much smaller volume than the spent fuel. Reprocessing, however, entails the production of other waste streams, Intermediate Level Waste (ILW) which can be quite voluminous, and additional health hazards to workers engaged in this sector of the industry. The arguments for and against the use of reprocessing are not clear cut in a global perspective; much depends on the strategic view of individual countries on the need for recycling resources.

5. ENVIRONMENTAL IMPACT

In normal day to day operation of a nuclear reactor there is very little emission of radioactivity. Oxides of sulphur and nitrogen are not produced, nor are there emissions of particulate matter nor of hydrocarbons.

All national authorities in countries using nuclear power have established laws which limit the discharge of radioactivity to the environment from all types of facilities. These laws and the detailed regulations underpinning them are based on very detailed scientific assessments of the effects of radiation on human health. Using these assessments of the health effects national regulatory bodies set conservative limits for radioactive discharges so that the general population as well as workers at the sites will not receive harmful doses. In all cases, the plant operators then set more conservative operating limits, the targets of operation being 10 to 100 times less than regulatory limits (in order to avoid reaching the limits set by law). Thus a sort of double conservatism is applied.

Special arrangements are made to ensure that none of the radioactive wastes created by the use of nuclear power cause unacceptable impacts on the environment. In addition to the HLW and ILW mentioned above Low Level Radioactive Waste (LLW) is created in much larger quantities, although a considerable part of this form of waste arise from medical, industrial and agricultural uses of radioactive substances. The UKAEA has published estimated for 1987 which set the world production of LLW, ILW and HLW at 314,000, 22,200 and 2,870 cubic meters respectively in addition to 8,920 cubic meters of spent fuel [6]. To put this in perspective the UK figure of a total of 46,000 cubic metres of radioactive waste has been estimated as about 1 per cent of all hazardous wastes produced in the country [7].

6. DECOMMISSIONING

In addition to the concern over the disposal of radioactive wastes, attention must be given to the fate of the reactor structures themselves. The core structure and parts of the cooling arrangements will become radioactive during operation of the reactor. Some parts of these structures can be decontaminated by cleaning the surface with appropriate chemicals. The waste fluid then needs to be handled as a radioactive waste, perhaps after some form of volume reduction. Other structures can be cut up and encapsulated for final disposal, probably as intermediate level waste. So far no large, commercially operated nuclear power plant has undergone a complete decommissioning programme although much relevant technical experience has been obtained in maintenance operations and in demonstration activities on smaller plants. Some of the early French, British and Canadian commercial reactors have entered into the first stage of decommissioning where it is envisaged that they will be made safe to be left under surveillance while residual radioactivity decays.

7. ECONOMICS

Since 1983 the NEA has undertaken three studies (the last in cooperation with the IEA and the IAEA)[8] to compare the cost of electricity production using nuclear or other means. The approach adopted has been to collect authenticated data, usually from utilities that intend to place orders for plants and have good quality estimates in hand. Using these data a calculation has been made of the discounted lifetime levelised cost of electricity production at the specified plant. This method computes the price of electricity at the plant boundary such that the stream of revenue exactly covers all the costs (of construction, operation, waste handling, decommissioning and all plant specific items) when all the cash flows are discounted at an appropriate rate. The ratio of this price for nuclear electricity to the price of that produced by other means within any one country is a good guide to the relative economics of the different sources, although more sophisticated appraisal techniques are used in preparing individual project decisions.

In the latest study cost data were obtained for 17 OECD and 5 non-OECD countries for plants which could be commissioned in the period 1995 to 2000. It was assumed that all plants would have a life of 30 years and a 72% levelised lifetime load factor (i.e. the ratio of power produced to the power available from operating the plant at full capacity for the whole time). At a discount rate of 5% (which was considered by many respondents as appropriate for public utilities) nuclear plants were projected to have a significant economic advantage over coal-fired plants for base load power production in Japan, the majority of OECD Europe and those regions of North America distant from coal fields (10% difference in cost was characterized as 'significant').

Several sensitivity analyses were conducted, confirming that the most important parameters were the discount rate and the expected price of coal. With a 10% discount rate and coal prices as expected by utilities, nuclear power had a cost advantage in 3 OECD countries, there was approximate comparability in 2 countries and in 4 coal had the advantage. At a lower coal price projection, suggested by the IEA's Coal Industry Advisory Board, and at the 5% discount rate, four countries showed a significant advantage to nuclear, four showed approximate equivalence and one showed a significant advantage for coal. Changing the discount rate to 10% at these coal price projections made coal-fired generation the cheaper option in most countries. On the cost and economic and other parameter assumptions used by the respondents in their own calculations, seven out of ten comparisons were in favour of nuclear power.

8. CURRENT POSITION

Nuclear power is used to produce electricity in 24 countries. Worldwide there is an installed capacity of 324.5 GW_e in 424 reactors. In 1990 they provided about 17% of all the electricity produced or about 5% of the world's total commercially traded energy. Four-fifths of the capacity is in OECD countries where some countries generate as much as 75% of their electricity in nuclear plants. Nuclear power reactors are under construction in a further four countries; two countries have built but not operated power reactors; and one country has withdrawn its operating reactors from service.

The fuel cycle for the industry is now well established for all but the final stages. Uranium is produced in 18 countries with economically viable resources believed to exist in 31. Uranium enrichment facilities for civil use are operated in seven countries with a few others having pilot plants. Fuel fabrication is undertaken in 15 countries. Spent fuel is currently stored at the reactor site for some time after its removal from the core but in addition there are spent fuel storage facilities 'away from reactor' in 7 countries. Reprocessing services are offered by two countries and a further five countries are understood to have operable or pilot reprocessing plants.

9. PROSPECTS

Governments in many countries see sound strategic reasons for including nuclear generating capacity in the future energy plans for their countries. In some countries the economic risks of nuclear power are seen as too great, also some countries do not have a need for additional large base load generation plants, the common use for nuclear reactors. In some countries the majority of the public lacks confidence as to the safety of operation of reactors and as to the possibility of confining radioactive wastes. These are among the reasons for the reduction in plans for nuclear development which have been seen in several countries over the last decade or so. Reduced forecasts of the growth of electricity demand in OECD countries have also contributed to the decline in placing of orders for nuclear plants as for all other forms of base load generation.

The conditions needed for the advancement of nuclear power differ between countries. In many countries there will be strong pressure for more nuclear development as long as the overall economics of nuclear power are favourable. Reactor vendors and fuel manufacturers are endeavouring to ensure that this continues to be possible with much attention to reducing the construction cost of nuclear power plants, this being the largest cost component. Several of the concepts now under development are in the medium size range (about 600 MW_e which gives them a better potential for deployment in countries where the electricity grids are still fairly small. A considerable effort is also going into the design of passively operated safety systems in order to reduce even further the small probabilities that equipment failures or the loss of emergency power supplies could jeopardize the safety of the reactor. It is envisaged that this will give the owners and financiers greater confidence that their investment will not be lost. It is also hoped that there will be benefits in terms of public acceptance.

Given the rate of political development in some regions and the close dependence of nuclear plans on political factors there is room for considerable uncertainty as to the amount of nuclear development to expect.

Over the next decade there is expected to be modest growth in nuclear generation capacity with a rise from 324.5 GW_e in 1990 to the range 450-580 GW_e in 2010 [9]. Most of this increase will be in industrially developed countries although the more populous and industrially advanced developing countries are planning to increase their investment in this energy source and additional countries are intending to have their first reactors operating within this period. The current nuclear technological and industrial base is expected to be capable of supporting a considerably greater rate of increase. Whether the industrial capacity will be called fully into play will depend to a large extent on the development of favourable public and political attitudes based on perceptions of such factors as security of energy supply, economic risks, environmental safety and nuclear safety.

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SOLAR THERMAL ELECTRIC TECHNOLOGY

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ABSTRACT: This paper describes the status and outlook of different solar thermal power generation technologies and resources. Technical characteristics of solar thermal systems are discussed. Also treated are environmental impacts and costs of solar thermal generating technology which are expected to be available between now and the year 2020. Some institutional and other barriers are pointed out which might delay the deployment of solar thermal power generating systems. Finally, recommendations of technology development priorities and the need and opportunities for international cooperation is stressed.

SUMMARY

Technology

Solar termal electricity generating systems utilize reflective surfaces to concentrate the incident direct proportion of the sunlight onto a receiver where it is absorbed into a working fluid that drives a thermal conversion/generator unit. Thermal solar plants operate most efficiently in the earth's equatorial belt of 30-40° N/S where direct insolation is highest and may operate also as heat and power (co-generation) units.

Three main types of concentrating collectors have evolved for use in solar thermal systems - low concentration (10 to 100 times) parabolic troughs, and high concentration (100 to 10000 times) parabolic dishes and central receivers. Higher concentration allows higher temperatures to be achieved in a working fluid and makes electricity generation more efficient.

Parabolic trough systems are the most mature of the thermal electric technologies. They require sun tracking in one axis and use parabolic surface reflectors to concentrate sunlight onto a fluid-filled receiver tube that is positioned along the line focus. The temperatures reached are typically about 400-500°C. Troughs are modular and in a "farm" thousands of identical distributed receiver modules are grouped together to produce large amounts of heated fluid, which is then transported to a nearby facility to generate electricity.

Parabolic dishes are point focus collectors and must track the sun's position in two axes. The heat absorbed by the receivers at the focal points of the dishes is either collected and transported to a central ground-mounted heat engine/generator set (dish farm system) or heat (Sterling) engines coupled to electrical generators are mounted directly at the focal points to produce electricity (dish/Sterling systems). Like the trough, the basic dish module is small and may be grouped into larger multimodule (distributed collector) systems, allowing flexibility in meeting requirements of various applications. An important technical feature for parabolic dishes is the ongoing development of mirrors using flexible stretched membranes, which allow adjustment of the radius of the curvature in order to focus the sunlight optimally. Eventually, this development is expected to result in lower material requirements and significant cost reductions.

Central receiver systems use a multitude of sun tracking mirrors (heliostats) to focus sunlight onto a single elevated central receiver (tower), producing tens or hundreds of megawatt of heat. This thermal energy is used in a nearby plant to generate electricity.

Potential unit capacity of thermal solar plants ranges between about 100 kW_t for single parabolic dishes and several hundred MWe for solar tower power plants, with parabolic trough plants situated in between. At an average presently efficiencies of thermal solar plants are about 15% with the potential to go up as high as 20-25% in the next thirty years.

Solar thermal systems are expected to be used in either a peaking mode without use of solar heat storage or with an integral thermal storage for intermediate and base-load plants yielding higher plant capacity factors and lower electricity generating costs. Also hybrid mode of operation with an auxiliary fuel (e.g. natural gas) may be used to provide dispatchability and achieve even higher capacity factors and lower cost of electricity delivered. Today typical capacity factors at plant sites in the solar belt are in the range of 35-40%.

In 1990, the world's total installed solar thermal power capacity was slightly over 310 MW_e (i.e. parabolic trough: 285 MW_e, parabolic dish: 12 MW_e, central receiver: 16 MW_e) with an accumulated operational experience of thermal solar power plants of about 300-500 MW_e.

Future R&D should be directed towards:

- Focusing development effort on the preferred concepts that have been identified
- Utilizing the technical infrastructure that remains, particularly the test facilities
- Applying the lessons learned from the projects already conducted
- Enhanced international cooperation in R&D and technology transfer.

The long term potential for electricity generation by solar thermal power plants is optimistically estimated to be not more than a few percent of the world's total installed electricity generating capacity in the target year 2020.

Environment

Under normal operating conditions, the most important environmental effects of solar thermal electric power plants relate to the land requirements of about 20-35 m^2/kW_e for these facilities and subsequent effect on local biota due to changes in soil structure, microclimate, etc. In dry and sunny climates where this technology is likely to be applied first, land availability is not expected to be a problem.

Solar thermal systems have no airborne emissions at the plant level. There is practically no waste from plant operation. Accidents with external consequences are negligible. Two unique hazards to health may arise, namely, from reflected light and from accidental release of heat transfer fluids.

Economy

The parabolic trough solar power plant (Luz SEGS, California), being the most mature of the solar thermal systems, is a demonstrated and established commercial system. For hybrid operation electricity generating costs of about US \$0.17/kWh_e have been quoted. Obviously, competitiveness to conventional power technologies, such as fossil and nuclear has not been reached.

In the given time-frame of 30 years the development and deployment of solar thermal systems for power production will be affected by environmental challenges, energy security concerns and economic competitiveness. The cost of solar thermal energy technologies is apt to be significantly lowered (target: US \$0.1/kWh_e or below) through continued development efforts, but the answers how far cost will decrease and how soon this will occur is fairly uncertain. In most of the long-term projections an optimistic view about the market penetration of the future is taken. Realistically, however, only a few percent of the world's total electricity generation will be coming from solar thermal power plants by the target year 2020.

There needs to be a balance among research, development and deployment strategies. Cooperation among utilities, engineering and equipment industries, regulatory agencies and research centres is a key element.

Large scale base load deployment of solar thermal technology still requires considerable development effort.

Enhanced international cooperation in R&D and technology transfer is required to facilitate implementation of the most efficient and least costly solar thermal technology. Thus, the establishment of ad hoc international mechanisms for information exchange and technology transfer is needed.

1. INTRODUCTION

The earth receives only a very small fraction of the total solar radiation, but even this amount greatly exceeds the energy used of mankind. It is also the ultimate source of other forms of renewable energy such as wind and hydroelectric.

The low intensity (about 1.37 kW/m^2 outside the earth's atmosphere) and its variation with timeat any point on the earth's surface may limit the ultimate contribution of solar energy to the total global energy mix.

Solar radiation or 'insolation' is divided into direct and diffuse radiation. Direct insolation from the disk of the sun is unscattered and can be concentrated to give higher insolation fluxes at a receiver.

Diffuse insolation results from scattering in the atmosphere and appears to come from the sky or reflections from the ground. The diffuse component may vary from as little as 10% to as much as 100% of the available source and cannot be significantly concentrated.

The sun's position in the sky, that is the geometry between the sun and a point on the earth's surface, varies both with the time of the day and the time of the year, yielding daily and seasonly variations of insolation and consequently of energy outputs. In addition weather patterns have a significant impact on the total energy available in a region and its specific variability. Dense cloud covers reduce the total insolation to nearly the diffuse component only. Thus, locations at roughly the same latitude may exhibit striking variations of insolation which has a direct impact on the cost of energy delivered by this resource.

Solar radiation also has a wavelength distribution equivalent to a black body with a temperature of 5800°K. The distribution covers the ultraviolet, visible, and infrared regions.

Consequently, the distribution of the solar energy spectrum at a specific location on earth varies, as the chemical species in the atmosphere absorb specific wavelengths and as the attenuation in the atmosphere depends on the elevation of that specific location.

Principally, two options are available to convert solar radiation into electricity. One option is utilized in solar thermal systems, where electricity generation is effected by using concentrated sunlight (direct radiation) to generate electric energy by thermodynamic processes by means of thermal conversion/generator devices. The second option uses photovoltaic semiconductor devices to directly convert sunlight (total radiation) into electricity.

The choice between thermal and PV systems for large-scale power production is not only a question of cost - which presently favours thermal systems but also of weather conditions, since concentrating systems require sunny areas. Clearly a non-concentrating PV system tends to maintain its output for reduced daily direct insolation because this reduction is accompanied by an increase in diffuse (sky) insolation.

Other aspects which may influence the choice of a solar power system are:

- Central receiver systems have their advantages in the multi MW_e-range only (because of economies-of-scale). For modular PV systems there is little economy-of-scale.
- Solar thermal plants are inherently more complex than PV systems.
- Economics.
- Constraints.

Solar thermal systems are expected to be used in either a peaking mode without use of solar heat storage, or with an integral thermal storage for intermediate and base load plants that have higher capacity factors and lower electricity generating costs. Also, a hybrid mode of operation with auxiliary fuel (such as natural gas) may be used to provide dispatchability and to achieve higher capacity factors with lower costs for the electricity delivered.

While the use of solar energy has been evolving over many years, modern research and development of solar power plant technology has only been going on for about 15 years in response to the first oil embargo. So far, the equivalent of about two to three billion US dollars has been spent worldwide in those countries involved in solar energy technologies.

The extensive research and development conducted over this period was reviewed in [1] to select those capabilities that should be retained and to identify continued research and development. Although the United States had been the focus of this review general results applicable to other countries or world regions could well be drawn. The valuable information provided by this review has been used extensively for the preparation of this report.

Three categories of system concepts have been identified as being potentially attractive for collecting and concentrating sunlight for electric power production. They are the central receiver, the parabolic dish and the parabolic trough and will be later discussed in detail.

2. EVALUATION OF SYSTEM FEATURES

Following [1] the approach for assessing the status of solar thermal electric technology was:

* Evaluate the technology according to its ultimate potential without regard to near-term economics.

* Evaluate energy for solar only operation. The effect of burning fossil fuel in a 'hybrid' mode is ignored since the solar plant would only be expected to become economically viable when its energy costs approximates the cost from a fossil-fuelled plant.

* Utilize the experimental data base from full solar thermal electric system experiments to the greatest extent possible.

* Select a preferred configuration to be representative of each of the three solar thermal technologies described above. The selection is to be based on (1) having an adequate

data base for evaluation of the system's performance and costs and (2) offering the lowest potential energy costs within a particular technology.

* Estimate upper and lower bounds for the energy costs for the selected system concepts such that the value for the mature commercial system would be expected to fall within these bounds with a 90% confidence level. The upper bound should represent existing experimental results and the current status of system definition. The lower bound should represent the predicted potential for the system so long as it is not contradicted by experimental data.

* Compare the energy costs for alternative concepts with a standard solar plant defined in terms of capital costs expressed in dollars per peak watt at a 25 per cent annual capacity factor and annual operation and maintenance costs of US $0.01/kWh_e$. This allows plants to be compared with each other and with alternative renewables with minimum dependence on changing economic assumptions.

* Assess the status of the technology for the three system concepts and estimate the development requirements to commercialize the system. The costs and time required for component and system development through demonstration of the commercial plant configuration are also estimated.

2.1 The central receiver system

In a central receiver system, a field of computer-guided heliostats (mirrors) focuses sunlight onto a tower mounted receiver. The concentrated heat energy absorbed by the receiver is transferred to a circulating heat transfer fluid to power an electric generator. Part of the heated fluid may be diverted to an energy storage subsystem that allows the power plant to operate during non-solar hours. A typical central receiver system is illustrated in Figure 1.

The central receiver has received the most substantial development support of any of the solar thermal electric concepts. This system concept in utility-scale electric power production has the following advantages: (1) Minimum 'plumbing' is required to collect solar energy from the field, (2) very high concentration of sunlight can be achieved which allows high efficiency both in energy collection and in its conversion to electricity and (3) large size installations are possible with a resulting economy-of-scale.

Solar components have been developed and improved over several successive 'generations', and a number of full system experiments have been built and tested to prove the basic system concepts, the most notable being the 10 MW_e 'Solar One' installation at Daggett, California on the Southern California Edison Company grid. System experiments included first generation systems which employed water/steam as the thermal transport fluid (like 'Solar One'), and advanced concepts, which used liquid sodium or molten salt for thermal transport. These experiments confirmed the technical feasibility of the concepts tested leaving some of the environmental aspects still to be dealt with.

2.1.1 System concepts

The major components of the central receiver system are:

* a collector subsystem which consists of a field of sun-tracking mirrors;
* a receiver which absorbs the reflected sunlight from the mirrors and converts it into thermal energy;
* a heat transport subsystem that circulates a heat transfer fluid through the receiver to extract the absorbed energy and transports it to either the storage or power conversion subsystems;
* a storage subsystem that stores the collected solar energy as sensible heat;
* a power conversion subsystem that converts the thermal energy into electricity like in a conventional plant for dispatch into the grid; and preferably
* a master control subsystem that coordinates the control of the different subsystems.

The collector field layout and the receiver configuration are interrelated. Selection of the heat transport fluid, the thermal storage media and the power conversion cycle and working fluid define the central receiver system concept.

2.1.2 Components

2.1.2.1 Heliostats

The heliostat could be a two-axis tracking assembly that reflects sunlight onto the tower-mounted receiver. It is the major component of the collector subsystem and represents the major cost element of the central receiver system. The heliostat assembly is comprised of reflector modules (mirrors), a support structure, drive units (2 axes) with gear boxes and motors, a controller, a pedestal and a foundation.

Field wiring for power and control, field controllers for a group of heliostats, an array controller for the entire field and support equipment complete the collector subsystem.

Because the heliostat is a totally new component and because of its major cost impact, substantial effort has been devoted to its development. Most of the development utilized glass mirrors with steel structural support; these are called glass/metal heliostats. Glass/metal heliostates are fully developed technically and have shown good performance and availability under test and in system experiments. The major issue remaining is the achievement of low cost (about US $100/m^2) under mass production.

An innovative design that could be lower in cost than the glass/metal heliostat is the stretched membrane concept. The principle of this design uses a mirror module consisting of a ring, front and back membrane, a tensioning system, and an active focus control system. The radius of curvature can be set at a range of values which allows this single mirror module to effectively focus the sun at exactly its slant range from the tower. By placing a slight vacuum in the plenum between the two membranes, the mirror module can be focussed onto the receiver. By placing a slight pressure, with respect to the atmosphere, in the plenum, the mirror module can be defocussed.

The major cost benefits for the stretched membrane heliostat compared with the glass/metal design are:

* lower weight, e.g. the mirror modules can be as low as one-fourth the weight of comparable glass/metal designs;

* fewer parts and pieces;

* potential for drive and foundation cost reductions with advanced rim drives.

Development of improved designs with lower material requirements and lower costs is continuing for both heliostat systems.

2.1.2.2 Receivers

Solar receiver designs, development and testing have progressed through early water/steam concepts to those employing the advanced receiver coolants (liquid sodium or molten salt) in a conventional tube/panel configuration and finally to an even more advanced concept in which the reflected solar energy is absorbed directly in the coolant (Table I).

2.1.2.3 Thermal Storage

Although thermal energy storage development is less critical than either heliostats or receivers, subsystem test programs were conducted in support of both the water/steam and molten salt systems (Table 1).

Two experiences with thermal storage systems:

* A 4 MWh_{th} storage system employing dual liquid (oil) and solid (rock/sand) media was built and tested to qualify this concept for 'Solar One' [4]. A thermocline was utilized to store both the hot and cold fluid in a single tank. Heating of the storage media was achieved by removing colder oil from the bottom of the tank, heating it with steam in a heat exchanger and returning the oil to the top of the tank. During heat extraction, the process was reversed. The tests were successful and this concept was employed in the 'Solar One' plant. Operation from storage with this type of system results in reduced power output and lower conversion efficiency because the pressure and temperature of the steam are much lower than the one available from the receiver. Higher efficiency operation from storage can be achieved if the fluid is stored at or close to the receiver outlet temperature. This is a major motivation in going to the 'advanced' heat transport fluids.

* A 7 MWh_{th} storage system employing molten nitrate salt was built and tested at the Central Receiver Test Facility (CRTF) in 1982 [5, 6]. It utilized 2 tanks to store the salt at 566°C and 288°C. A fossil-fired heater was employed to simulate a solar receiver, and an air cooler simulated a steam generator. The test program

demonstrated that a molten salt thermal storage system could operate efficiently, reliably and safely in all modes expected for a solar power plant. This storage system was subsequently utilized in the Molten Salt Electric Experiment (MSEE) at the CRTF.

2.1.2.4 Other Subsystems

A molten salt-heated steam generator was designed and constructed at the CRTF [7]. It was incorporated into the Molten Salt Electric Experiment and was tested and evaluated as part of that program.

An on-going program is testing large-scale pumps and valves for use with molten salt [8, 9]. It is hoped that the continuing development and test program will resolve all problems and confirm the technical capability of transporting molten salt at the scale required in a commercial plant.

The balance of the central receiver system utilizes conventional technology and equipment, so little component development was conducted apart from the full system experiments.

Many of the system experiments, most notably 'Solar One', conducted significant development of solar plant controls as part of their total program. In fact, these developments contributed to the application of distributed digital controls to conventional power plants. The most significant result from the system experiments reveals that the power produced was much lower than predicted. 'Solar One' was the only plant with a net positive output of electricity, and it produced substantially less than the predicted output. The major technical accomplishments from the central receiver development programs are given in Table I, representing the status of central receiver system technology using water-steam and advanced system concepts.

2.1.3 Presently preferred central receiver system concept

In a utility solar central receiver study [12, 13, 14] a presently preferred central receiver system concept has been worked out and is summarized Table II. This preferred receiver concept predicts superior performance and lower cost compared to other central receiver concepts evaluated. However, the energy cost predictions for this presently preferred design concept exhibit a high uncertainty. Major factors are:

- Net annual electrical energy production is highly uncertain. Data from system experiments employing molten salt for thermal transport are inadequate to either confirm or contradict the performance predictions. In fact, daily (24 hour) net positive output of electrical energy was never achieved for any of the advanced system experiments (employing either molten salt or liquid sodium for heat transport) despite very positive advance predictions. This result can be attributed to inadequacies of the experiments rather than to a fundamental deficiency of the technology, but it leaves the performance predictions unconfirmed. Consequently, current predictions of high performance are based on analytical simulations without experimental verification.

Table I System experiment projects on water/steam and advanced system concepts

	WATER/STEAM SYSTEM EXPERIMENTS				ADVANCED SYSTEM CONCEPTS		
	SOLAR ONE	CESA-1	EURELIOS	MSEE	MSS/CTE	THEMIS	IEA-CRS
LOCATION	Calif., USA	Tabernas, Spain	Sicily, Italy	New Mexico, USA	New Mexico, USA	Targasonne, France	Tabernas, Spain
PROJECT PARTNERS *(for abreviations see [1])*	DOE, S.Calif. Edison Co., L.A. Dep. of Water & Power, Calif. Energy comm.	Spanish Ministry of Industry & Energy, SENER, INITEL, CASA, EISA, Tecnicas Reunides	CEC, ANSALDO, ENEL, CETHEL, MBB	DOE, EPRI, Industry	DOE, Industry, utility, Sandia National Lab., B & W	COMES, EDF, CNRS, CETHEL	IEA, DFVLR, INTER ATOM, Sevillana (= Spanish utility)
PLANT NET RATING	10 MW_e	1.2 MW_e	1 MW_e	750 kW_e	5 MW_t	2.5 MW_e	500 kW_e
HELIOSTATS							
Number	1818	300	70/112	211	211	201	93
Size, m^2	39.1	39.6	52/23	37.2	37.2	53.7	39.3
Total area, m^2	71064	11880	6216	7849	7849	10740	3655
Field configuration	Surround	North	North	North	North	North	North
RECEIVER							
Configuration	External	Cavity	Cavity	Cavity	Cavity	Cavity	Cavity & Exposed panel
Tower height, m	55	60	77	61	61	100	43
Coolant	Water/Steam	Water/Steam	Water/Steam	Nitrate Salt	Nitrate Salt	Hitec Salt	Sodium
Outlet temp., °C	516	525	512	566	566	430	530
Outlet press., bar	105	108	62				
THERMAL STORAGE							
Type	1 Tank, Thermocline	2 Tanks	3 Tanks	2 Tanks	2 Tanks	2 Tanks	2 Tanks
Media	Oil/Rocks/Sand	Hitec Salt	Hot Water/Hit. Salt	Nitrate Salt	Nitrate Salt	Hitec Salt	Sodium
Rating, MWh_t	135	18	0.36	7	7	40	5.5
POWER CONVERSION							
Type	Turbine	Turbine	Turbine	Turbine	None	Turbine	Steam Motor
Working fluid	Steam	Steam	Steam	Steam		Steam	Steam
Inlet, °C, bar							
From receiver	510, 100	520, 98	510, 62	504, 72		410, 40	500, 100
From storage	274, 28	330, 15	410, 19 - 7				
Heat rejection	Wet Cool. Tower	Dry Cool. Tower	Wet Cool. Tower	Air Cooler		Dry Cool. Tower	Wet Cool. Tower

Table II Preferred central receiver system concept

Plant rating	200 MW_e
Plant type	Solar only
Solar multiple [1]	1.8
Heliostat design	150 m^2 stretched membrane
Total reflective area	1.8 x 10^6 m^2
Field configuration	Surround
Receiver type	External cyclinder
Receiver coolant	Molten nitrate salt
Thermal storage type	Hot and cold tanks
Thermal storage medium	Molten nitrate salt
Storage capacity	5-6 hours
Power conversion	Reheat steam turbine
Land area	10 km^2

Note: 1) Ratio of maximum solar thermal power collection rating to that required to match the plant rating.

- The high freezing temperature of the molten salt heat transport and storage fluid, 221°C, creates a number of technology issues which have not been resolved fully.

- The cyclic operation of the receiver and 'conventional' equipment exceeds the capability of many commercial grade components.

- System costs are uncertain due to the early stage of equipment development and the conceptual level of the system design.

The lower and upper limits for annual conversion of sunlight to electricity were estimated to be 8% and 17% respectively. The lower limit was derived using both the efficiency of thermal energy collection in a molten salt system experiment and the full system efficiency of 'Solar One'. If the preferred salt system does not prove capable of achieving this value, there is high confidence that an advanced water/steam configuration could achieve the 8% efficiency which was selected as the lower limit. The upper bound for annual efficiency is based on a prediction employing simulation of annual operation with favorable assumptions for performance and availability.

The cost for the installed commercial system was estimated to range from US $206/$m^2$ to US $443/$m^2$ of reflective surface area. The lower bound corresponds to cost estimates of the conceptual system design including the reductions expected from development of an advanced heliostat concept. The upper bound represents a current budgetary cost estimate of this design which includes all contingencies on the capital and operation and maintenance costs appropriate to the early stage of development and the limited design detail. The capital costs include the capitalized operations and maintenance differential from the standard plant.

Combining the lower limit of performance with the upper limit on costs yields:

- The confirmed energy cost is equivalent to that from the standard solar plant having a cost of US $4.85/$W_p$. With a fixed charge rate of 0.105 and annual insolation of 2500 kWh/m^2/a, this corresponds to a levelized energy cost of US $0.243/kWh.

Combining the upper limit of performance with the lower limit on costs yields:

- The potential energy cost is equivalent to that from the standard solar plant costing US \$1.10/W_p. With the same assumptions as above, this yields a levelized energy cost of US \$0.061/kWh.

Significant development remains to bring this concept to commercial readiness. Highest priority should be given to:

- Reduction in the uncertainty of the annual net electricity output.
- Resolution of technical issues associated with the molten salt fluid and the resulting impact on system costs.

If these issues are resolved favorably, development should proceed with (1) completion of component and equipment development, (2) scale up to commercial size and (3) demonstration. The potential of this system concept warrants continued development in a phased program.

2.2 Parabolic dish systems

Parabolic dish systems use point-focusing collectors that track the sun in two axes and focus radiant energy onto a receiver at the focal point of the parabolic concentrator. Energy transferred to a heat transfer fluid circulating through the receiver can be converted directly into electrical energy by using a heat engine/generator coupled to the receiver, or the thermal energy can be transported to a central location for conversion to electrical energy. This concept shares the capability of very high concentration with the central receiver system. It differs in that the sunlight is concentrated onto receivers distributed throughout the collector field. Thus, the energy must be collected from the field before it can be dispatched to the user. Accordingly, it is often called a distributed receiver system. Potential advantages of this system type for utility-scale power production include:

- Highest possible optical efficiency due to always being pointed directly at the sun.
- High thermal and power conversion efficiencies due to the high concentration of sunlight.
- The capability of mounting small heat engine/alternator sets a at the focus of the dish. This can provide a modular system and minimum thermal losses upon system cooldown.

2.2.1 System concepts

Two distinct types of system concepts have been utilized with dish concentrators. One employs centralized conversion of thermal energy to electricity; the other generates electricity right at the dish.

2.2.1.1 Central generation

The dish system concept employing central generation of electricity is similar to the central receiver system expect that energy is collected from the field in the form of a heated fluid rather than as reflected sunlight. The major elements are:

* The concentrator is a two-axis tracking reflector assembly that collects and concentrates sunlight at the focal point.

* The receiver absorbs the reflected sunlight and converts it into thermal energy.

* The heat transport subsystem circulates a heat transfer fluid through these distributed receivers, extracts the absorbed energy and transports it to a central location.

* The thermal storage subsystem stores the collected energy as sensible heat.

The power conversion subsystem converts the thermal energy into electricity.

The requirement to circulate throughout the concentrator field limits the choice of heat transport fluid to those that would not freeze upon cooldown to ambient temperature. This in turn limits the maximum temperature of the working fluid, hence power conversion efficiency.

The alternatives of trace heating the thermal collection piping or of employing thermochemical transport have been proposed. Neither have been developed; for dish systems and either would add substantial complexity.

2.2.1.2 Distributed generation

The dish system concept employing distributed generation locates power conversion equipment at each dish concentrator. This allows collection of energy from the field to be in the form of electricity rather than as a heated fluid. The principle of this concept is illustrated in Figure 2.

The concentrator can be the same as in the central generation concept, but it must be matched to the rating of the power conversion unit.

The power conversion unit is normally a close-coupled, packaged assembly, mounted on the concentrator, which consists of:

* A receiver, located at the focus of the concentrator, that absorbs the reflected sunlight and heats the working fluid of the heat engine.

* A heat engine which converts the thermal energy into mechanical work.

* An alternator or generator coupled to the heat engine that converts the work into electricity.

* A heat rejection system which rejects the waste heat from the engine to the atmosphere.

* Controls to match the engine's operation to solar availability.

Parabolic dish systems do not require a thermal storage. The electricity generated is directly fed into a central grid. Plants with distributed generation will be evaluated in the sun-following mode; they could be hybridized to operate with fossil fuels during periods without sunshine. Among the components of the system thermal transport is virtually eliminated; instead, electricity must be collected from each engine in the field. Most significant for this concept is the relatively complex power conversion unit which must be replicated thousands of times throughout the field for a utility scale power plant. Its capital cost, operating reliability and maintenance are major issues in assessing this system concept.

Development of dish components and systems is much less extensive than for the central receiver. However, many system studies have been conducted of various dish system concepts [18, 19]. Full system experiments were conducted with dish systems employing both central and distributed power generation [1].

2.2.2 Components

The present status of parabolic dish systems may be described as the demonstration phase of this technology; the Distributed Receiver Test Facility (DRTF), located adjacent to the CRTF in Albuquerque, New Mexico, is the major center for component testing of dish systems.

2.2.2.1 Dish concentrators

The dish concentrator is a two-axis tracking assembly that reflects and concentrates sunlight onto the focus point of the dish. It is functionally and physically similar to the heliostat except for the following two differences:

* Pointing Direction. The dish concentrator must always be pointed directly toward the sun during operation.

* Reflector Module Curvature. Since each dish concentrates to its own point focus, the reflector modules must approximate a truncated paraboloid.

Dish concentrators have received much less development support than has been devoted to heliostats. However, many of the lessons learned from the heliostat development program have been applied. Most notably, the evolution to larger heliostat sizes and the transition from glass/metal to stressed membrane designs are paralleled in the dish development program.

Three generations of concentrators have been developed and tested. Table III summarizes the characteristics of first generation, second generation and advanced concentrators.

Major attention is currently being given to stressed membrane concentrators as most likely to achieve the goals of low production costs and adequate performance. Solar Kinetics, Inc. has designed a single membrane dish and produced a 1.8 meter diameter model membrane assembly. Together with the LaJet innovative concentrator, both single and multiple membrane designs are available for further development and evaluation.

Table III Three generations of development of concentrators

	Test Bed Concentrator	Shenandoah	Sulaibyah	White Cliffs	Vanguard	MDC/USAB	LEC-460	PKI	Acurex Innovative	LaJet Innovative	SKI Advanced	Advanced Membrane
Location	New Mexico, USA	Shenandoah, Georgia, USA	Kuwait City, Kuwait	White Cliffs, Australia	Calif , USA	Calif , USA	New Mexico, USA	Kansas USA	New Mexico USA	New Mexico USA	New Mexico USA	Stuttgart Germany
Manufacturer	E Systems	Solar Kinetics, Inc	Messerschmitt Bölkow-Blohm	Austr Nat University	Advanco	McDonnell Douglas	LaJet	Power Kinetics	Acurex	LaJet	Solar Kinetics	Schlaich & Partner
Type	Parab Dish	Parab Dish	Parab Dish	Parab Dish	Parab Dish Multi Facets	Parab Dish Multi Facets	Stret Membr Multi Facets	Square Dish Sec Concentr	Parab Dish	Stret Membr Multi Facets	Parab Dish	Singe Stret Membr Dish
Concentrator Diameter, m	11	7	5	5	10 6	11 0	9 5	13 2	15 0	19 6	14 0	17 0
Reflector Area, m^2	97 1	38 0	18 3	19 6	91 4	91 0	43 7	135	177	184	154	227
Reflector Material	Silvered Glass	Alumin Poly mer (FEK 244)	Silvered Glass	Silvered Glass	Silvered Glass	Silvered Glass	Alumin Mylar (ECP-91)	Silvered Glass	Silv Polymer (ECP-300X)	Silv Polymer (ECP-300X)	Silv Polymer (ECP 300)	Silv Glass Mirror Tiles
Reflector Assembly	224 Mirror Facets on Foam Glass Substrate	21 Aluminum Sheet Metal Petals	Reinforced Plastic Dish	Fiberglass Shell (2300 Mirror Tiles)	336 Mirror Facets on Foam Glass Substrate	82 Curved Mirrors on Stamped Steel Back Struture	24 Reflector Membranes on Al Frames, by Vacuum	360 Mirror Facets in Venetian Blind Arran.	80 Panels of Alumin Stell, Stamped Back Sheet	95 Membranes on Curved Frame, Shaped by Vaccum	30 Curved Al Parab Gore Panels,Sand wich Design	Double Steel Stret Membr over Steel Ring, Vaccum
Structure/ Mounting	*Parab Shaped* Tubes, Alidade Structure	Al Ribs, Steel Hubs, Tripod Mount Structure	*Concrete* Pedestal	*Tubular* Steel Frame, Steel Pipe Pedestal	*Truss Frame/* Pedestal Encased in Concrete	*Trusses/* Beams/Steel Pedestal	Truss Structure/ Concrete Pier	Space Frame/ Secondary Support/Box-beam Track	Rib Trusses/ Rings/Hub/ Tripod Support	Spaceframe Tripod Assem Anchor Fittings	8 Radial Arms 2 Rings, Hub/ Tubular Steel Pedestal	Steel Support Girders on Ring Turnable Base
Tracking Axes	Elevation-Azimuth	Polar Declination	Polar-Declination	Elevation-Azimuth	Elevation-Azimuth	Elevation Azimuth	Polar-Declination	Elevation-Azimuth	Elevation-Azimuth	Polar Declination	Elevation Azimuth	Elevation Azimuth
Concentration Ratio	3800	234	678	1000	2700	8000	24 to 2000	700	2434	1100	1226	600
Number Built	2	114	56	14	2	6	700	1	1	1	1 Gore	3

2.2.2.2 Engines for distributed generation

The most challenging requirement of the dish system concept with distributed generation is the development of a complete Power Conversion Unit (PCU) on the scale of a single dish (25-50 kW_e) with the following characteristics:

* Low Capital Cost (Goal is US \$300/kW_e or US \$7500 for a 25 kW_e unit)

* Low Maintenance Cost (Goal is US \$10/m^2/a or about US \$900 per year for a 25 kWe unit)

* High Conversion Efficiency (Goal is 41% for PCU, 28% for system).

* Capability of unattended operation.

Different engine cycles have been investigated for this application with most attention being given to the Stirling cycle [15].

2.2.2.3 Stirling cycle engines

The Stirling engine has many similarities to the technology used in a conventional internal combustion engine. It differs, however, in that heat is supplied externally and continuously to heat a gas (hydrogen or helium), which is contained in a completely closed system. The Stirling engine has an engine block that contains cylinders and pistons. It converts heat energy to mechanical energy by means of the alternating compression and expansion of confined gas. Heat is added to the working fluid during the expansion stage, and heat is rejected during the compression stage.

Residual heat energy is recycled through a regenerator. The regenerator stores a large portion of the heat of the working gas after expansion and returns the heat to that gas as the gas flow reverses direction.

The pistons in the Stirling engine have two functions: they move the gas back and forth between the hot and the cold locations displacement), and they extract mechanical work from the engine. There are two basic classes for the displacer and power piston configuration: kinematic and free-piston.

* The kinematic engine has the pistons attached to an output drive shaft.

* The free-piston engine has displacer and power pistons that are free to move within the engine and are not physically attached to each other.

2.2.2.4 Other engines for distributed generation

Other engine cycles which received significant development support for distributed generation with the dish concentrator include an organic Rankine cycle [16] and the reciprocating steam engine [17]. Development of these two concepts continued into 1988 for use in two small Community Solar Experiments.

2.2.3 Presently preferred parabolic dish system concept

Selection of the preferred dish system concept involves the successive selection between central and distributed power generation, and then, selection of the preferred concept. On the basis of the system studies and system experiments evaluated, distributed power generation is selected over central power generation for dish systems. Reasons for this selection are:

* The system experiments with distributed power generation achieved substantially higher energy production per unit concentrator area than the potential of the systems with central generation.
* High thermal inertia, with a daily cooldown and warmup of the piping system and distributed receivers, is a serious limit on the annual energy collection capability of a system with central generation.
* The potential for high temperatures (hence high conversion efficiency) of the dish system is limited by the thermal collection fluids available with central generation. Fluids that do not freeze at ambient temperatures have either of the following limitations: (a) moderate maximum temperature capability or (b) high pressure and/or change of phase with water.
* The distributed power generation system allows unattended operation.
* The distributed power generation system is modular with a wider range of application.

Additional advantages of the presently preferred Dish Stirling concept are:

* High performance as has been demonstrated in the experimental test programs.
* Rapid warmup/startup and good response to cloud transients have been achieved.
* Part load efficiency is high.
* The engine and power conversion unit (kinematic Sterling engine) are more fully developed than the alternatives.

The lower and upper limits for the annual conversion efficiency of sunlight to electricity were estimated to be 16% and 28% respectively. The lower limit is based on field test data from two test programs. The upper limit is a prediction based on expected improvements in efficiency and availability.

The equivalent capital cost for the installed system was estimated to range from US $263/m^2 to US $933/m^2. The lower bound is based on the composite of several cost estimates for the future mature commercial system and includes the development of advanced dish concentrators. The upper bound is based on the current system design with contingencies appropriate to the early stage of development. It should be noted that more than 50% of the equivalent capital cost in the upper bound represents the present value of the annual costs for operation and maintenance. The uncertainty in this cost element is extremely large.

Combining the lower limit of performance with the upper limit on costs yields:

* The confirmed energy cost is equivalent to that from the standard solar plant having a cost of US \$5.11/W_p. With a fixed charge rate of 0.105 and annual insolation of 2500 kWh/m^2/a, this corresponds to a levelized energy cost of US \$0.255/kWh.

Combining the upper limit of performance with the lower limit on costs yields:

* The potential energy cost is equivalent to that from the standard solar plant costing US \$0.82/W_p. With the same assumptions as above, this yields a levelized energy cost of US \$0.049/kWh.

Significant development remains to bring this concept to commercial readiness. Initial effort should concentrate on the reduction in the uncertainty of operation and maintenance costs.

The current reference kinematic Stirling engine has had substantial development, but maintenance requirements and costs are uncertain due to limited field testing. Resolution of this issue by extended testing is required in order to assess the adequacy of this design for the solar application. If required, potentially superior engine concepts have been designed, but they are at a much earlier stage of development.

If sufficiently low maintenance costs can be confirmed for one of the candidate engine designs, development should proceed with (1) completion of engine development, (2) development of the concentrator, (3) integration of the engine and concentrator into a system module, (4) development of a multi-module system and (5) demonstration.

The potential of this system concept warrants support of the first stage of engine development and testing.

2.3 Parabolic trough system

Parabolic troughs are U-shaped collectors lined with reflective material that concentrate sunlight onto a linear receiver tube positioned along the focal line of the trough. A fluid in the receiver is heated by the absorbed radiant energy and then transported to a central point for conversion to electrical power. Parabolic troughs are distributed receiver systems with central power generation. Because the focus is along a line rather than to a point, the concentration factor of the sunlight is much lower than for either the central receiver or dish systems (typically 40-80 compared to 500-1000). Thus, this concept is expected to have lower collection and power conversion efficiencies than either the dish or central receiver. Potential advantages of this system type for utility-scale electric power production are (1) the trough reflector and drive system has the potential for very low cost and (2) the system can be configured to be relatively simple and well within the current state-of-the-art.

Troughs are the most fully developed of the three solar thermal system concepts. Much of this development was directed toward systems producing industrial process heat. A major installation of commercial solar thermal electric power plants (Luz SEGS) is now in operation in California.

2.3.1 System concept

The parabolic trough collector assembly consists of:

* Reflector panels which are parabolic shaped mirrors that concentrate the sunlight onto the receiver.

* A receiver assembly that absorbs the reflected sunlight and heats a transfer fluid. The receiver is normally a tube with a high absorbance/low emissivity coating enclosed within a glass tube. The low emissivity coating reduces radiative thermal losses and the covering tube reduces convective losses. The absorber tubes must have flexible end connections to accommodate their motion during the daily tracking cycle.

* A drive unit to track the sun in one axis.

* Structural supports and foundations.

* Controls.

Troughs are mounted so that the absorber is horizontal. They can be oriented either east-west or north-south. The north-south orientation normally provides slightly higher yearly energy but its winter output is very low. The east-west orientation provides a more constant output throughout the year. Four types of reflector structures (stamped sheet metal, sheet molding compound, sagged glass/steel frame and honeycomb sandwich) were built and tested in the course of the Performance Prototype Trough Development Project [20].

The system employed for electric power production generally consists of:

* The controller subsystem including the receiver assembly.

* A heat transport subsystem which circulates a heat transfer fluid through the receivers and transports the collected thermal energy to a central location.

* A thermal storage subsystem which stores the collected energy as sensible heat.

* A power conversion subsystem which converts the thermal energy into electricity and rejects the waste heat.

Test and evaluation programs for trough systems include the Industrial Process Heat Program [21] and the Coolidge Solar Powered Irrigation Project [1] both undertaken in the USA. For the European Community the reference pilot plant is located in Tafbernas, Spain and is run under the auspices of the IEA.

2.3.2 Solar electric generating system (SEGS)

A series of solar electric power plants based on trough collectors are being placed in service on the Southern California Edison Company grid. The developer made use of favorable power purchase agreements under the Public Utility Regulatory Policy Act (PURPA) and tax benefits available at the federal and California state levels. The plants were sold to third party financial ventures structured to maximize the value of the tax benefits and cash flow from electricity sales. Additionally, the developer provided performance guarantees of the plants' output and low interest, non-recourse note financing to help leverage the investors' rate of return. By these means, the previously described technology development has been commercialized.

The solar collector fields are designed and manufactured by Luz Industries, Israel, who also performs the bulk of the conceptual and preliminary system design engineering of the plants. Luz Engineering Corp. coordinates engineering activities in the USA, performs the operations and maintenance functions at the sites and conducts the marketing and financial activities for the projects.

The Luz parabolic trough system design utilized the extensive design and development activities carried out by the United States Department of Energy over the years 1975-1984. The Luz contribution has been to complete this development into practical systems and to commercialize them.

A listing of the first seven SEGS plant»s is given on Table IV. SEGS I and II are located adjacent to Solar One in Daggett, California, SEGS III, IV, V, VI and VII are located at Kramer Junction, California.

Table IV SEGS plants

SEGS plant number	Net rating (MW_e)	Date in service	SEC Power Purchase Agreement
I	13.8	12/84	Negotiated
II	30	12/85	Negotiated
III	30	12/86	Standard offer #4
IV	30	12/86	Standard offer #4
V	30	9/87	Standard offer #4
VI	30	9/88	Standard offer #4
VII	30	12/88	Standard offer #4

Note: Standard offer #4 provides fixed energy and capacity payments for the first ten years. The on-peak period rates are particularly high, notably during the key summer months from June through September.

It can be seen that these first seven plants represent nearly 200 MW_e of net installed capacity. The use of a parallel, fossil heat source allows these plants to obtain full capacity credit and to maximize power production during peak periods, thus achieving maximum revenue. The current low price for natural gas further enhances economics.

Table V shows the system evolution in the plant characteristics of SEGS I, III and VII.

The net electrical output from the SEGS plants is purchased by Southern California Edison (SCE) under the power purchase agreements cited in Table IV.

Prices quoted for representative SEGS plants by Luz are shown on Table VI. It should be noted that these are selling prices, dictated by the market, not costs.

The most impressive achievement of the SEGS program, among many, was the learning from the first plant(s) which was applied to improving subsequent plants. Despite the advanced state of the technology at the beginning of this program, SEGS I and II were plagued by numerous problems. These were fixed, as well as possible, for the affected plants, but the lessons learned were applied to the later plants. This resulted in extremely rapid and effective technology development as product improvement.

2.3.3 Trough system status

Parabolic trough systems are in an entirely different category than either of the proceeding system concepts. Several large hybrid trough plants are operating in California as a commercial venture and more plants are being installed. They made use of (1) a relatively advanced technology base, (2) the ability to burn natural gas to supply 25% of the plants' thermal energy, (3) favorable power purchase agreements and (4) federal and state tax incentives.

Following startup of the first plant in late 1984, subsequent plant design incorporated improvements based on the lessons learned from the first plant's operation. This has been a most impressive product improvement program and has brought the trough system to an advanced state of development.

Performance and capital costs for this system are based on the existing installations and the improvements planned for subsequent plants. The bounds for annual collection and conversion efficiency are 9% and 12%; the bounds for capital costs are US $\$355/m^2$ and US $\$515/m^2$. There is a much lower range to these limits than for either of the previous concepts because of the more advanced state of development. Combining the limits on performance and costs yields that the confirmed and potential energy costs from this system concept are equivalent to those from the standard solar plant at costs of US $\$5.00/W_p$ and US $\$2.59/W_p$ respectively. The corresponding levelized energy costs are US \$0.25/kWh and US \$0.134/kWh.

The potential of this concept is substantially lower than that of either the central receiver or the dish systems. This is due to the lower concentration of sunlight achievable with the trough which results in lower collection temperatures and lower power conversion efficiency. The confirmed energy cost is in the same range as the confirmed energy costs for the other two systems.

Because of its advanced state of development, further development is not required at this time.

Table V SEGS plant characteristics

	SEGS I	SEGS III	SEGS VII
Plant net rating (MW_e)	13.8	30	30
Collector Type Total area (m^2) Field configuration	 LS-1, LS-2 106 512 North-south	 LS-2 203 980 North-south	 LS-3 176 580 North-south
Thermal transport Fluid Fluid outlet temperature (°C)	 ESSO 500 307	 Monsanto VP-1 349	 Monsanto VP-1 393
Thermal storage Type Media Rating (MWh_{th})	 2-tank ESSO 500 117	None	None
Fossil fuel subsystem Rating (MW_{th}) Fuel Configuration	 8.5 Natural gas Series Superheater	 88 Natural gas Parallelboiler Superheater	 84 Natural gas Parallelboiler Superheater/ reheater
Power conversion Type Working fluid Inlet conditions Solar: Temp. (°C) Press. (bar) Fossil: Temp. (°C) Press. (bar)	 Turbine Water/steam — — 416 35.3	 Dual admission turbine Water/steam 327 43.4 510 105	 Reheat turbine Water/steam 371 100 371 100

Table VI SEGS plant prices

SEGS I	US $4493/kW$_e$	US $865/m^2
SEGS III	US $3500/kW$_e$	US $515/m^2
SEGS X (projected)	US $2000-2250/kW$_e$	US $355-400/m^2

2.4 Summary of system features' evaluation

A summary evaluation of the three systems is given in Table VII which also includes estimates of the development cost and time required to bring the systems to commercial readiness.

Table VII System comparison

	Trough	Central receiver	Dish Sterling
Cost (US $/m^2)	355-515	206-443	263-933
Net annual efficiency (%)	9-12	8-17	16-28
Energy cost equivalent to stand. plant (US $/$W_p$)	2.6-5.0	1.1-4.8	0.8-5.1
Levelized energy cost (UScents/kWh)	13-25	6-24	5-25
Development cost (10^6 US $)	0	100-500	50-200
Development time (years)	0	15-20	10-20

The progressive improvement in the systems' potential for producing low cost energy can be seen in moving from the trough to the dish system. A corresponding increase in the uncertainty band is also apparent.

It should be noted that the dish Stirling system was evaluated in the sun-following mode; no energy storage is provided. The trough system was also evaluated without storage; if required, thermal storage could be provided without excessive penalty. The central receiver system provides six hours of operation from storage. Variations in storage capacity can be provided by the central receiver system with little impact on energy cost.

Since the central receiver system size is inherently large, the cost and time for each development and scaleup step are likely to be large. This is reflected in the development cost range and is a major impediment to its development and commercialization. The small module size of the dish Stirling system allows less costly and more rapid development through successive product improvement cycles.

The lower limits of the development costs are estimates based on a highly successful program conducted in a favorable demand climate (rising fossil fuel prices). The costs for development of the dish Stirling system assume that either the existing engine proves adequate or that an improved engine is developed for other applications, such as for automotive propulsion, space power or as an auxiliary power unit.

For comparative purposes Table VIII from [2] is included here, showing projected electricity generating costs of central receiver and parabolic trough systems in the time span from 1990 to 2025. Comparing the values of Tables VII and VIII, only partial agreement can be observed, due to the differences of the assumed cost structures and assumptions.

Table VIII Projected electricity generation costs in UScent/kWh of central receiver and parabolic trough systems [2]

		1990	2005	2025
Central receiver	1)	46-78	14-24	8-14
	2)	29-50	11-18	7-11
Parabolic trough	1)	22-36	11-18	8-14
	2)	17-28	9-15	7-12

Notes: *1) plant site: Spain*
2) plant site: North Africa

lower bound: discount rate 4%, total life time depreciation
upper bound: discount rate 8%, half of life time depreciation

3. OVERALL ASSESSMENT

3.1 Technology

Substantial development has been accomplished for solar thermal electric technology [10, 22, 23, 24, 25]. A vigorous initial worldwide program produced many technical achievements and developed a strong infrastructure with capable technical personnel together with supporting analytical tools and test facilities; this vigorous program has not been maintained.

Three potentially viable system concepts have been identified:

- The Luz SEGS trough

- The molten salt central receiver (with a backup of water/ steam)

- The dish Stirling system.

The Luz SEGS trough is a demonstrated commercial system as a hybrid plant burning natural gas. The data base for water/steam central receivers is extensive, but the greater potential of the molten salt system justifies assigning a higher priority to its development.

Neither the central receiver nor the dish Stirling system is technically ready now. Both have substantial uncertainties that must be resolved prior to consideration of commercialization.

The potential of the central receiver and dish Stirling systems warrant further development.

The development time required to commercialize either of these two systems is likely to be comparable with the time remaining before fossil fuel prices increase to a level that would make these alternatives economic. There is danger that the technical infrastructure will be lost in the near future if the trend of a limited perceived need for renewable energy continues.

Future long-term potential for utilization of solar thermal power plants is highly dependent on the possibility to achieve economic competitiveness with conventional power plants. In most of the long-term projections an optimistic view about the market penetration of the future is taken. If in this context total installed solar thermal power capacities in the range of say 30-50 GW_e will be achieved by the target year 2020, then this will be only a few percent of the world's total installed electricity generating capacity.

R&D efforts should be directed towards:

- Focusing development efforts on the preferred concepts that have been identified utilizing the technical infrastructure that remains, particularly the test facilities
- Applying the lessons learned from the projects already conducted.

3.2 Environment

Under normal operating conditions, the most important environmental effects of solar thermal electric power plants relate to the land requirements of about 20-35 m^2/kW_e for these facilities and subsequent effect on local biota due to changes in soil structure, microclimate, etc. In dry and sunny climates where this technology is likely to be applied first, land availability is not expected to be a problem.

Pollutants (emissions) arising during plant operation are relatively minor and can be controlled by methods that are used routinely in the industry.

Two unique hazards may arise to health, namely from reflected light and from the accidental release off heat transfer fluids. Accidents with external consequences are negligible. There is practically no waste from plant operation.

The cumulative primary energy consumption for manufacturing and constructing solar thermal power plants has been assessed to be 8000 kWh/kW_e [2]. Central receiver systems should be able to reach values of below 5000 kWh/kW_e in the distant future. If an intended storage operation with 3600 full power hours per year can be reached, then energy-pay-back times of 1.5 to 3 years are achievable [2].

The metallic material requirements of solar farm concepts (distributed receivers) are quoted [2] to go up as high as 1250 t/MW_e. For the material intensive collector field with its tubing for the heat circuit (without power plant) of parabolic trough systems values of 120 t of steel/MW_e and 330 t of concrete/MW_e can be reached at present. For the central receiver system the metallic material requirements are in the range of 600-1000 t/MW_e. The specific values for the total material requirements are quoted to be 2500-5000 t/MW_e. No shortages of any of the required materials can be envisaged in the next 60 years [2].

3.3 Economy

* The Luz SEGS trough is a demonstrated commercial system as a hybrid plant burning natural gas.

* The central receiver and the dish Stirling systems offer the potential of producing electricity at a cost of about 5 cents per kilowatt hour (equivalent to the standard solar plant costing US $\$1/W_p$). These are very attractive costs for a renewable energy resource.

- The uncertainties in potential energy costs are higher than might be expected after the extensive development already accomplished. Most of the reasons can be traced to the near 'crash' growth rate of development programs following the first oil embargo. Many projects were conducted in parallel to investigate different system concepts. This produced an effective screening process which helped to select the preferred concepts, but accomplished only limited development of the preferred concepts.

The economic prospects (target electricity generating costs: US \$0.1/kWh$_e$ or below) for solar thermal electricity will depend largely on the success gained in improving efficiency and on the possibility to achieve economic competitiveness with other electricity generating technologies. The annual efficiency with which sunlight is converted to electricity is a function both of conversion efficiency when the plant is operating and of plant availability. With technical improvements, this annual efficiency could be raised by about 20% above the current levels of thermal systems. There is considerably more potential for cost reduction, by a factor of two to three in the long run, in central receivers and parabolic dishes than in parabolic troughs, which have a more mature technology and come closer to their technical efficiencies [23, 24, 25].

3.3.1 Parabolic troughs

Although specific investment costs (based on SEGS experience) can not be quoted at present electricity generating costs of parabolic trough solar power plants are about US \$0.17/kWh$_e$ for hybrid operation and about US \$0.2/kWh$_e$ for solar-only mode operation. In the medium to long-term generating costs of about US \$0.1/kWh$_e$ are expected to be reached, with specific investment costs of about US \$2000-2500/kW$_e$.

3.3.2 Parabolic dishes

According to the present technology status and based on specific investment costs of about US \$5000-6000/kW$_e$ electricity generating costs of dish/Sterling solar power plants are in the range of US \$0.25-0.35/kWh$_e$. With advanced technology generating costs as low as US \$0.1/kWh$_e$ are believed achievable in the medium-term, with specific investment costs of about US \$2500/kW$_e$. USA evaluations even suggest electricity generating costs as low as US \$0.05 \$/kWh$_e$, with specific investment costs as low as about US \$1000/kW$_e$ in the long-term.

3.3.3 Tower solar plants

According to published data present investment costs for commercial tower power plants rated 100-200 MW$_e$ (including a six hour daily heat storage) and an annual capacity factor of about 35-40% are in the range of US \$2200-5000/kW$_e$ yielding electricity generating costs in the range of US \$0.08-0.25/kW$_e$. The uncertainties in these cost figures is evident. Long-term investment cost decreases in the future are expected to bring the specific investment costs down into the range of US \$1100-2000/kW$_e$ due to economy-of-scale effects resulting in electricity generating costs as low as US \$0.06/kWh$_e$.

Solar thermal electric systems generally require the availability of high-grade maintenance staff resulting in O&M costs of about 5%/a.

3.4 Factors influencing market deployment

The market deployment of solar thermal power technologies is also influenced by factors such as economic and financial (e.g. slow replacement rates of existing stock of power plants limits introduction of renewable energy technologies; high initial costs and long payback times may be a high financial risk; limitations on investment capital may slow down power plant construction programmes), regulatory and institutional constraints (e.g. regulations may accelerate or decelerate technologies to be deployed; electricity tariff regulations may enhance or hinder introduction of renewable technologies), utility requirements and capabilities (e.g. size and sophistication of a utility influence the introduction of future power options, as advanced technologies require specialized manpower and industrial capabilities) and last but not least by public acceptance (e.g. more attention must be given to public concerns with regard to technology options; solar energy exhibits to a large extent public support) [24].

4. RECOMMENDATIONS

* Maintain the trough technology already developed.

* Maintain industry interest and as much of the technical infrastructure as possible by continuing development of the most promising concepts (on a non-crash basis) through the present period of limited immediate need.

* Preserve the 'Solar One' facility for the next phase of central receiver development.

* Initiate the next phase of central receiver development with the objective of reducing the uncertainty in potential energy costs from the current value of 4 to 1 to a target value of 2 to 1.

* Initiate the next phase of dish Stirling system development with the objective of identifying the preferred Stirling engine design and confirming annual maintenance costs.

* Allocate all of the limited solar thermal electric funding E resources to the development of the preferred system concepts.

* Apply the lessons learned from prior projects to define and conduct the most effective programs.

* Adopt the perspective that the development and introduction of a new technology capable of supplying a significant part of our electrical generating capacity will take an additional 20 to 40 years.

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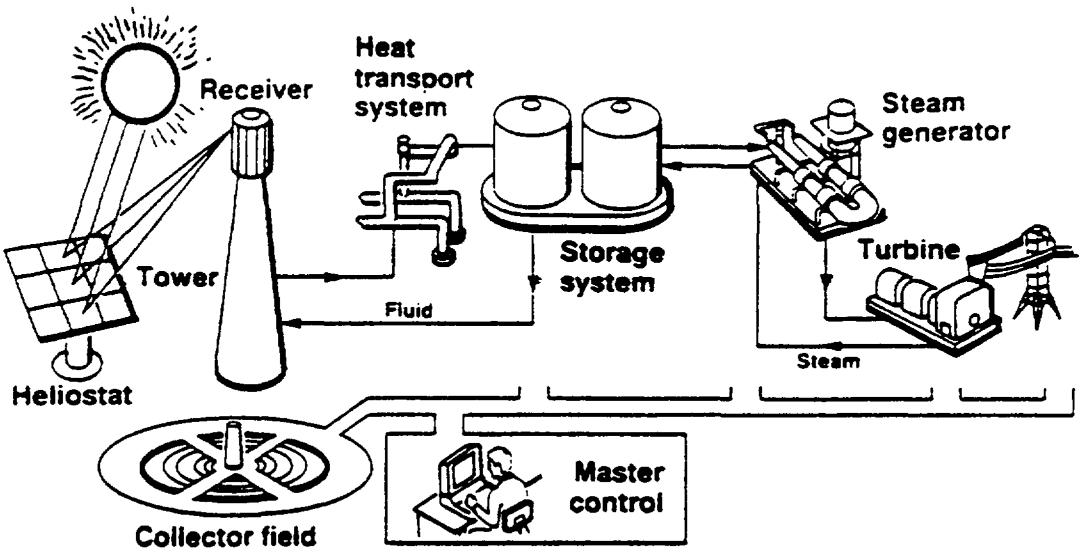

Fig. 1 Solar central receiver system [3].

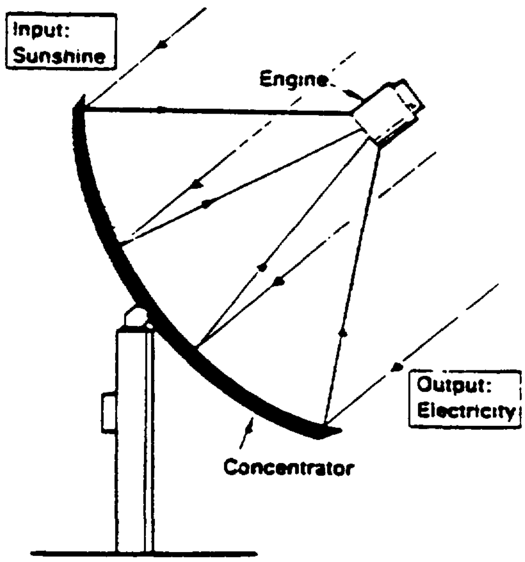

Fig. 2 Principle of dish system with distributed power generation

SOLAR PHOTOVOLTAIC ELECTRIC TECHNOLOGY

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ABSTRACT: This paper describes the status and outlook of different solar photovoltaic power generation technologies and resources. Technical characteristics of solar photovoltaic systems are discussed. Also treated are environmental impacts and costs of solar photovoltaic generating technology which are expected to be available between now and the year 2020. Some institutional and other barriers are pointed out which might delay the deployment of solar photovoltaic power generating systems. Finally, recommendations of technology development priorities and the need and opportunities for international cooperation is stressed.

SUMMARY

Technology

Photovoltaic power generation is based on the conversion of direct and diffuse sunlight into electricity using photovoltaic cells. Photovoltaic cells are most commonly made from silicon, but they can also be made from gallium arsenide, cadmium telluride and copper indium diselenide. Many cells are placed together in modules which can be flat plates or concentrators, using devices to increase the light intensity that reaches the cell. Plant system sizes are, in principle, unlimited and could, theoretically, range to up to 1,000 MW_e. At present, however, they range, typically, from a few kilowatts to a maximum of roughly 5 MW_e; this is dictated by the capacity of the inverter systems on the market.

Presently, the estimated peak power of all photovoltaic plants installed worldwide (exclusively single and multicrystalline technology) is about 150 MW_e. To date, the accumulated operational experience for photovoltaic plants is approximately 100-200 MW_e.

At present, cells made of single crystalline superpure or polycrystalline silicon slices are used commercially. Thin film amorphous silicon cells, produced on a continuous basis, have lower efficiencies, but they also cost less than crystalline silicon cells. However, some problems still arise with the long term stability of amorphous silicon cells. Polycrystalline thin film solar cells have recently been developed with cell efficiencies of more than 10%, exhibiting long term stability. Another technology, the tandem solar cell, uses two stacked photovoltaic cells of different types, thereby better exploiting the incident solar energy spectrum. Cell efficiencies above 30% have been reached, but further development is needed.

The efficiencies of today's flat plate modules range roughly from 5-15%, while concentrator modules have efficiencies in the neighbourhood of 20%. Annually averaged overall efficiencies for photovoltaic power plants are currently in the range of 6-8% and may possibly reach 20 or 25% by 2020. Present lifetimes range from a few years for some of the newer technologies to 20 years or more for polycrystalline silicon modules. As grid connected photovoltaic plants usually do not have storage systems,they are peak load plants and the maximum capacity factors are less than 30%, equivalent to about 2,500 hours of sunshine per year.

Environment

Production of photovoltaic generator s can involve hazardous gaseous, liquid and solid substances, as in other semiconductor industries. Past experience with these materials in related industries has shown that application of the available controls can reduce potential hazards from these materials satisfactorily. Great care will have to be taken in the disposal of such toxic materials from photovoltaic manufacturing, as well as the disposal of solar cell modules at the end of their useful lifetime, in order to minimize environmental impacts. During their operation, photovoltaic systems discharge no gaseous or liquid emissions or heat and are therefore considered ecologically benign.

Land requirements for PV systems are about 35-80 m^2/kW_e. Land most suitable for large central station applications lies in areas where annual insolation is high. Other factors such as regional energy demand and proximity to population centers may influence siting decisions and possible local disturbance of micro-climate.

Economy

Because photovoltaics are based on thin film and semiconductor technologies that lend themselves to mass production, their economic potential is substantial. Technological breakthroughs could lead to a decrease in module costs by a factor of up to five because of the improved conversion efficiency of the production scale-up of solar cells, along with design optimization and series production of other system components. Such an improvement in module costs could make the cost of photovoltaic power fairly competitive with fossil fuelled alternatives. In addition, since solar cells have relatively few geographical site restrictions, no moving parts, and no need for cooling water, they may prove to be an attractive alternative to solar thermal electric power despite their somewhat lower annual capacity factor.

Because of the difficulties in storing solar energy on a large scale and over periods of more than a few hours, the grid connected plants must be regarded as economizers of fuel rather than as an absolute replacement, and this affects the economic viability of PV technology.

Investment cost consists of module cost (about 60%), balance-of-system (BOS) costs (about 30%; area- and power-related costs) and engineering (about 10%) cost. In the past 10 years, module cost has decreased from US \$50/W_p to less than US \$6/W_p. Medium-term goals (1995-2000) are US \$1.0-2.5/W_p for flat-plate modules and US \$0.7-1.8/W_p for concentrator modules. With volume production and novel technologies (e.g. thin film) long-term module costs as low as US \$0.3-0.5/W_p for flat-plate modules and US \$0.3-0.4/W_p for concentrator modules are predicted. BOS costs are in the range of US \$2-4/W_p and will decrease less than module costs in the future.

Present total system costs are in the order of US \$10/W_p. Medium-term (5-10 years) system costs are estimated to be US \$2.5-5/W_p, while long-term system costs (by the year 2020) are predicted to decrease to about US \$1/W_p.

Photovoltaic solar power plants are currently estimated to have generating costs of about US \$0.5-0.6/kWh_e. Assuming a 30 MW_e/a photovoltaic module production in a single manufacturing facility, generating costs as low as US \$0.2/kWh_e are calculated for 2,400 h/a full-load operation. The long-term goal for electricity generating costs of about US \$0.06/kWh_e has been projected to be achieved before the year 2020. O&M costs of photovoltaic solar power plants are very low namely in the range of 0.1%/a (US \$0.005/kWh_e) to 1.5%/a.

Factors Influencing Market Deployment

The present terrestrial photovoltaic market has three major segments-consumer products, remote power, and utility generation. The current rapid growth rate in photovoltaic sales (about 30%/a) is almost exclusively because of the increase in sales for remote power. There is growing acceptance and recognition of photovoltaics as a reliable and economic remote power source.

The current utility purchases for photovoltaics are relatively small. Utilities are investigating this new electricity generating technology both for their own use (large-scale) and to learn how it interacts with their system; for example, if homeowners chose to interconnect their own photovoltaic system (small-scale) with the utility grid. Because of the photovoltaics consistent progress over the past decade utilities have expectations for continued technological progress leading to higher efficiencies, longer lifetimes, and lower cost.

Photovoltaics is a new and practically untried technology. Its future is promising but uncertain. The technical success of photovoltaic plants can be predicted based on the physics of photovoltaic devices and on foreseen technology developments. Photovoltaics has been demonstrated to work, and it will become inexpensive. However, at this point it is hard to project market penetration 30 years into the future. Many investigations have been carried out to project the potential impact of photovoltaic technology on both regional and global energy supply. The primary difference between these assessments was the timing of the cost reduction necessary for the impact to occur, and the resultant rate of market penetration. Although, all assessments involve subjective judgement, in essence, all the studies assume the basic tenet for significant market penetration of photovoltaic power, an energy cost of approximately USc 6 to 12/kWh is necessary for economic operation in the utility environment. Hence, even if in 2020 twice as much PV plant capacity as that quoted for solar thermal plants were installed, this would not exceed a few percent of the global installed electricity generating capacity.

1. INTRODUCTION

The earth receives only a very small fraction of the total solar radiation, but even this amount greatly exceeds the energy used of mankind. It is also the ultimate source of other forms of renewable energy such as wind and hydroelectric.

The low intensity (about 1.37 kW/m^2 outside the earth's atmosphere) and its variation with time at any point on the earth's surface may limit the ultimate contribution of solar energy to the total global energy mix.

Principally, two options are available to convert solar radiation into electricity. One option is utilized in solar thermal systems where electricity generation is effected by using concentrated sunlight (direct radiation) to generate electric energy by thermodynamic processes by means of thermal conversion/generator devices. The second option which will be treated in this review is called photovoltaics (PV) and uses photovoltaic semiconductor devices to directly convert sunlight (total radiation) into electricity.

The choice between thermal and PV systems for large-scale power production is not only a question of cost - which presently favours thermal systems - but also of weather conditions, since concentrating systems require sunny areas. Clearly a non-concentrating PV system tends to maintain its output for reduced daily direct insolation because this reduction is accompanied by an increase in diffuse (sky) insolation. Another aspect which may influence the choice of a solar power system is the fact that solar thermal central receiver systems have their advantages in the multi-megawatt (electric)-range (because of economies-of-scale). For modular PV systems there is little economy-of-scale. Moreover, solar thermal plants are inherently more complex than PV systems.

Photovoltaics attributes include features such as: (1) high modularity, (2) simplicity and low operating and maintenance costs, (3) environmental acceptability, (4) suitability for a wide range of product markets, both now and in future and (4) continuing technical progress.

While the development of PV was primarily technology-driven five years ago, a transition is now under way such that PV prospects are now becoming primarily product-driven. The bulk power application has been viewed as the ultimate market in developed countries with good sunlight resources. Over the next five to ten years, however, other markets, smaller in size but offering higher value per unit of sales, will very likely become of great significance.

Nonetheless, a substantial amount of activity is under way within the electric utility industry worldwide aimed at understanding PV status and outlook; and in some cases, at fostering its introduction into utility use.

Accordingly, this report deals almost exclusively with grid connected PV power systems. Although it is often argued that on the long run central PV power stations will represent the largest share in any PV power system integrated into an electrical grid, it is believed that for the sake of objectivity decentral smaller grid coupled PV systems must also be considered. The valuable information provided in Ref.[1] has been used extensively in preparing this report.

1.1 Energy source

By means of the photovoltaic effect solar radiation (but also light from artificial sources) can be transformed into electricity. The amount of electricity produced depends on the geographical location, on the hour of the day, the season of the year and finally on the local weather conditions. The global solar insolation is the sum of the direct and the diffuse radiation.

The maximum solar insolation (at sea level) is about 1 kW/m^2 and the total yearly thermal energy incident on one m^2 is about 800 to 2,600 kWh depending on the geographical location. In order to study the characteristics of different PV generator materials it is essential to know the spectral energy distribution of the solar radiation which depends on the incident angle of the radiation [2, 3, 4, 5, 6].

1.2 Photovoltaic principle

If light which has entered a semi-conductor diode is absorbed then a voltage is induced between the two poles of the diode. If an external circuit exists then current flows and electrical energy is supplied. The induced voltage depends essentially on the used semi-conductor material while the induced current is proportional to the magnitude of the incident and absorbed solar radiation. A semi-conductor diode which has been manufactured specifically for conversion of light to electricity is called a solar cell. Such a cell always supplies direct voltage cells lie typically between 4 and 25% [2, 6].

Typical solar cells have a size of about 100 cm^2; such cells yield about 1 W_p (peak watt) of electrical power at full sunlight.

1.3 Photovoltaic systems and components

The basic element of a PV system is the generating module which produces electrical energy. A PV module consists of a number of solar cells switched together, typically ¼ to 1 m^2 in size, and yields peak power values of 30 to 120 watts at full solar insolation.

Groups of modules can be switched together to form larger fields. By means of this modular extension PV systems of any size can be achieved without problems.

Two principle types of PV modules are employed. The *flat plane module* where the whole irradiated area is covered with solar cells; and the *concentrator PV module,* with its optical elements (mirrors, lenses) which concentrate the incident light onto a small area. Only this small area is equipped with solar cells allowing important savings of the expensive semiconductor material [6].

Flat plane modules convert both direct and diffuse solar radiation, while concentrators use only direct radiation. Thus, the latter ones have always to be directed to the sun's position by means of mechanical tracking devices. Obviously, if flat modules are designed to track the sun then their efficiency is also increased. But this effect is rarely used.

The other system components of PV systems are conventional ones. They are the support structures for the modules and the electrical components for transformation and conditioning of the produced electricity. The design of these components is based on the type of the PV system applied [6,7].

Usually, electrical energy supply must be adjusted to the demand characteristics of the consumers. Small stand-alone systems run on direct current as it is produced by the PV system. They utilize simple controllers. However, very often energy storage is required for these systems in order to be able to supply uniform electrical energy. Typical electrical energy storage devices are lead batteries. Storage significantly increases system costs [6].

If alternating current (AC) is required then an inverter is necessary to invert the direct into alternating current. AC systems can be either stand-alone or grid connected systems. Small AC systems are mostly grid coupled so that the grid acts as storage for surplus electrical energy and thus allows compensation of the fluctuating solar insolation and the corresponding electricity generation. Large grid coupled PV systems feed all of the produced electricity into the grid.

Grid connected PV plants are required to exhibit specific requirements with respect to quality of the supplied electricity (voltage, frequency, harmonics content, nonlinear distortion factor) and with respect to safety measures. This necessitates certain design standards of the electrical system components leading to higher material requirements.

For the purpose of completeness it should be pointed out that besides battery storage and grid coupling also hybrid systems may be utilized. In these systems the solar generator is connected parallel to a second generator, for example to a diesel engine. In periods of poor solar insolation this second generator takes over the electricity supply. Usually, these hybrid systems work without storage systems.

2. TECHNOLOGICAL STATUS AND DEVELOPMENT TRENDS

2.1 Solar generator

The status of a specific PV technology is generally evaluated according to three about equally weighted criteria, namely: (1) conversion efficiency of solar cell, (2) manufacturing costs of module and (3) its technical lifetime. All three areas are subject to intensive research and development at present.

2.1.1 Solar cell types

Today for power modules almost exclusively solar cells based on mono- or multi-crystalline silicon are utilized [8, 9, 10, 11]. They are characterized by high efficiencies, great robustness and are based on a mature technological status. Silicon remains the most thoroughly investigated and used semi-conductor material. By means of large research and development efforts the quality of the silicon material could be improved continuously. However, the production costs could not be reduced by the amount desired, mostly because of lack of mass production. Should larger production outputs be achieved, new manufacturing processes which are in development at present will become economical, e.g. the ribbon processes for the production of silicon foils from molten material which could replace presently applied sawing techniques [12, 13].

As alternative approaches to the 0.2 mm thick crystalline silicon cell a number of thin film (0.002-0.03 mm) technologies are presently investigated. In 1989, the amorphous silicon (a-Si) has reached a fairly high market share of about 35%. Amorphous silicon cells are largely used for the power supply of small (mostly indoor) appliances. It is doubtful, if amorphous silicon will eventually be used outdoors on a large scale for power supply applications. Despite large research efforts no satisfactory high conversion efficiencies could be reached until now and the problem of decreasing efficiency (degradation) at solar radiation exposure could not be solved. This led to increased R&D efforts relating to other thin film technologies, such as copper-indium-diselenide (CIS), gallium-arsenide and cadmium-telluride. Although the results achieved are promising the commercialization has not yet commenced.

Table I shows the present (1990) development status of various solar cell materials. Gallium-arsenide exhibits theoretically the highest conversion efficiency but is very expensive. Also multijunction cells are listed in Table I; they utilize a larger portion of the solar energy spectrum and thus yield higher efficiencies than single cells. However, multi-junction cells are still in the stage of laboratory development.

2.1.2 Module technologies

Mono- or multi-crystalline solar cells are electrically switched (connected) together to larger units in order to obtain useful power ratings. These switched units (strings) are then covered with plastic foils and placed behind glass for protective purposes. This process of laminating yields a product, the module, which can be easily mounted and is weather resistant. For protection the edges of the module are equipped with a metallic frame. It became apparent, that this relatively costly technique with its high material requirements (glass, plastics, metal) can hardly be replaced, because only the hermetic encapsulation of the cells will yield the desired module lifetime of 20 years [6, 7].

The structures of thin film modules are significantly different. For economical manufacturing it is advantageous to dispose the cell material on large plane glass surfaces and to proceed with the structuring and forming of the cell contacts. If these modules are to be used outdoors, then again an efficient encapsulation has to be provided. Thin film structures are generally even more vulnerable to corrosion than crystalline silicon cells [6, 7].

Table I Development status of different solar cell technologies

	Laboratory		Power application		Production status
Size, efficiency	cm^2	%	cm^2	%	
Silicon					
Monocrystalline	8	22.6	100	16.0	++
Concentrator	0.15	27.5	26	17.2	++
Multicrystalline	100	17.8	100	13.5	++
EFG-Band	50	14.7	50	13-14	+
Dendritic web	4	17.0	8	15.5	(+)
Thin film cell	1	15.7			
a-Si (monojunction)	1	11.5	1000	5-8	++
GaAs					
Monocryst. on GaAs	0.05	29.0	4	17.0	+
Monocryst. on Substr.	1	17.6	4	16.5	+
Concentrator	0.5	29.3			(+)
Polycryst. thin film	8	8.8			
II-VI-Compounds					
CdS/CdTe	1	10.9			
CdZnS/$CuInSe_2$(CIS)	3.5	14.1			
Tandem structures					
Amorphous	1	13.7	1000	8.2	+
a-Si/CIS	4	15.6			
Si/GaAs	0.3	31.0			
GaAs/GaInP	1	27.6			
GaAs/GaSb	0.05	37.0			

++ *large scale production*
\+ *small scale production*
(+) *pilot production*

2.1.3 Solar generator characteristics

As presently concentrator modules are not available for market deployment most emphasis will be given to flat modules which are available on the market. Flat modules are characterized by their conversion efficiencies at full solar insolation (1 kW/m^2, spectral distribution at air mass 1.5) and at a module temperature of 25°C. The efficiency refers to the total module area and not to the active solar cell area and is about 75-80% of the single cell efficiency as given in Table I. For system design it is important to realize that the efficiency of a solar cell decreases with increasing module temperature. This is especially valid for crystalline silicon. Modules used in hot regions on hot days will be less efficient.

A series of carefully executed tests have proven that presently manufactured modules based on crystalline silicon exhibit lifetimes of at least 20 years, probably even 30 years. Furthermore, no degradation whatsoever has been detected. Limits of lifetime have to be attributed to corrosion phenomena of the module materials glass, metal and plastics. Therefore, all system analyses for PV energy scenarios are based on lifetimes of 20 to 30 years and assume a certain amount of module replacements due to failures, fractures or other mechanical damage. According to experience the module replacement rate is about 0.2%/a.

The utilization of amorphous silicon in power modules causes considerably more difficulties. Up to now all commercially sold a-Si-modules have shown degradation effects, which seem to be of principal nature. This has caused rather restricted application of these types of modules in larger PV systems.

In comparison, thin film materials such as CIS demonstrated much higher stability. Therefore, great efforts are undertaken to develop this type of thin film material to reach market maturity soon.

Other important characteristic design parameters for the construction of PV systems are: size, weight, mechanical stability and the manner of fixing of the module. Today, for instance, a typical module has the size of 107x76 cm^2, with a thickness of 2 cm at the frame and weighs about 6.5 kg. The frame may be screwed to the supporting structure but also clamping devices may be used.

2.2 System development

PV solar generators have been utilized in a variety of systems in a wide power range (μW for watches, MW for power plants). For large scale electricity generation purposes systems with rated electrical power smaller than 1 kW are not relevant. In fact, it is likely that grid coupled PV plants (central or decentral) will dominate electricity generation on the large scale because they do not necessarily require electrical energy storage systems which are prohibitively expensive.

In grid connected PV systems the second most essential component (after the solar generator) is the inverter. Despite the fact that the inverter represents a conventional component, there is still substantial development effort required. Conventional inverters exhibit rather unfavourable behaviour if they are operated in the partial load region (decreased conversion efficiency, higher losses). Because PV systems operate most of the time in the partial load region the efficiency of the conventional inverter averaged over a longer time span will be rather low. This fact has led to the initiation of developments of new types of inverters for PV systems. Until now, however, only prototypes are available at rather high prices. Only series production of this PV specific inverter will yield extensive application of this device at decreasing costs.

In other areas of power (current, voltage) conditioning there are practically no new developments necessary. Both in the area of cabling as well as for switches and safety equipment conventional elements and components can be used. Lightning protection equipment and measures, however, may become a significant cost factor especially in large PV plants when high safety standards are required.

The mechanical and civil engineering components of PV power systems represent substantial cost factors. Solar generators are large surface components, which usually are mounted with a certain angle to the horizontal plane and directed to the south. Customarily support structures made out of galvanized steel or wood are used, in some cases also concrete construction elements. Because often these support structures have to withstand high wind and snow loads, they must be designed and constructed accordingly and must have good foundations.

Land requirements for PV plants are considerable. As per installed kW peak power with an assumed (crystalline) module efficiency of 10% about 10 m^2 module area is required, land requirements are about 35 m^2. For less efficient (thin film) modules and less favourable geographical locations with respect to solar insolation land requirements may be as high as 80 m^2/kW_e. Because today the costs for solar generator support structures are in the range of US $120-250 per m^2 of module area these costs for conventional mechanical and civil engineering hardware strongly affect the overall system costs. Improvement of this situation is possible by the following means:

- As costs of support structures are strictly proportional to module surface area, higher module efficiencies in the future will proportionally reduce area (land) requirements.
- Massive support structures may be replaced by lightweight structures or eventually by stretched cable structures. Experiments in this direction are presently carried out.
- PV modules can fairly easily be integrated into the existing structures (roofs) of houses and buildings. On the one hand these structures can serve directly as support structures for the modules (e.g. flat roofs etc.). On the other hand modules may also serve a civil engineering function (roof covering, cladding panels for facades).

In all mentioned cases construction simplification and consequently cost reductions will result in the future. Thus, the need for further work and development in this area is required.

3. PRESENT APPLICATIONS AND MARKET SITUATION

3.1 Types of application

The PV generator is applicable in many ways, due to the variability of its size. In addition, due to its modular arrangement systems of any desired power rating can be set up.

Today four areas of application dominate the PV market: (1) commercial stand-alone systems (communication, signalling technique, cathodic corrosion protection, etc.), (2) stand-alone systems in the housing sector (lighting, water pumping, cooling, etc.), (3) grid coupled plants (private and industrial sector, power plants) and (4) small appliances (watches, computers, battery loading devices, etc.)

The issue of large central PV power systems versus small decentral PV systems will not be discussed in detail. It is likely to assume that both development paths will eventually contribute substantially to the overall share of grid connected PV generating capacity worldwide. From utilities' point of view, larger plant unit sizes are desirable allowing higher feed voltages to the grid.

Until now practically only pilot and demonstration plants up to a capacity of about 6 MW have been assembled [17, 19, 20, 21]. The present PV share of about 5% of grid coupled systems is not very high. However, it will be precisely grid coupled PV plants which of all PV systems will contribute most to electricity supply in industrialized countries. If the forecasts of the price developments will turn out to be valid, then a strong increase of the PV market share for grid connected systems will take place starting at about the year 2000. This development could in several countries strongly be influenced (accelerated) either by governmental fiscal measures or by environmental legislation. Thus, accurate forecasts are irrelevant [18].

3.2 Solar module fabrication

As the fabrication processes of crystalline and amorphous silicon are fundamentally different they will be treated separately.

Crystalline module fabrication is based on three more or less well rounded technological processes:

- Production of the silicon wafer,
- Solar cell technology,
- Module manufacturing.

In the production of Si-wafers two different production paths have been followed. One followed the technology applied in electronics industry. Thereby semi-conductor silicon is used to grow single crystals by applying the Czochralski process. Then the single crystals are cut into Si-wafers. The other process is a metallurgical one, whereby the silicon is cast into big blocks. The silicon solidifies exhibiting a multicrystalline, e.g. very coarse grain polycrystalline structure. Again, this material has to be sawed into Si-wafers.

Three cost factors are essential for the final price of the Si-wafer: the price of the basic material silicon, which at present is about US $30-50 per kg, the costs of crystallization, the block casting process being significantly cheaper than the Czochralski process, and the costs of Si-wafer sawing. Today the sawing process represents an obstacle. As silicon is very hard it can almost exclusively only be cut by using diamond saws. Thus, almost all of the silicon is cut by means of the usual diamond internal hole saw as used in electronics semi-conductor technology. This very costly process is now being slowly replaced by using multiwire saws, which manage to cut many wafers simultaneously. The wire saw not only leads to a cost reduction but also yields thinner Si-wafers thus reducing the silicon input. Moreover, thinner wafers exhibit higher conversion efficiencies.

Other processes which yield Si-wafers without the necessity of using a sawing step are in the stage of development. At present 6 different techniques for the production of silicon foils are investigated, three alone in Germany. If this development turns out to be successful than significant cost reductions will result.

The solar cell technology of crystalline silicon comprises three essential steps: the diffusion of a p/n-junction, actually the active structure; the attachment of metal contacts and the application of an anti-reflective layer in order to improve light penetration. Intensive efforts are going on to proceed with the further development of solar cell technology leading to continuous increases of the conversion efficiencies of solar cells. This development will continue and for manufactured cells efficiencies of 18% are expected by the year 2000. The end of this development can not be foreseen as is today evident from laboratory experiments. Drastic cost reductions will only then be realized when the solar cell production units will have reached significantly larger output capacities than today.

The same holds true with respect to anticipated cost reductions of module manufacturing. The steps of module manufacturing are soldering or welding of the solar cells to strings, laminating of cells in plastic and glass and module framing. Significant cost shares are the plane glass and labor. Large turnovers will lead to price reductions of glass and increased automation helps to avoid manual work and thus will reduce labor costs.

The technology of amorphous silicon is entirely different. Here the cell structures consist of a number of different thin layers with plane glass being the substrate. Over an oxide layer (tinindium oxide) at least three differently doped layers of amorphous silicon are applied followed by metallic contact layers. For protection again encapsulation is provided. The various layers are applied by different techniques, the a-Si layers, for instance, by means of reactive plasma deposition. The expense of apparatus is very high. This and the low deposition rates together with the low yields from the expensive process gases are the reasons that the production costs of amorphous modules did not fall below those of the crystalline modules as yet.

The other thin film technologies are in the development stage and not yet available on realistic production scales.

3.3 Development of turnover and market prices

It has become customary to measure the amount of modules sold in peak watt (W_p). This is appropriate in the case of power modules but very arbitrary in the case of thin film modules for small appliances with most of their application taking place at low light levels. As primary interest is given to grid connected PV power production the quantity W_p will be used.

Today about 45% of all solar cells use monocrystalline silicon, about 25% multicrystalline silicon and about 30% amorphous silicon.

In 1983 the world's annual turnover of 14 MW of PV modules has surpassed the 10 MW mark and since then is continuously increasing. The average annual rate of increase in the years from 1983 to 1988 amounted to 16%, the turnover in 1988 was about 30 MW. All signs seem to confirm the continuation of this trend. Supposing the previously quoted constant growth rate, this would lead to PV module production figures of 80 MW in 1995 and about 160 MW in the year 2000. The cumulative amount of modules sold - today being 150 MW - would amount to well over 1 GW in 2000.

This development implies a significant increase of the production capacities. Today production capacities are about 60 MW/a and are exploited to over 60% (over 80% in USA) in the case of crystalline silicon and to about 40% (about 20% in USA) in the case of amorphous silicon. For equal turnover increases as in the past years the present production capacities will be exhausted in 1993. This would be the latest point in time to start up new production facilities. Only a few companies have as, yet reported about production capacity increases.

Regarding the prospective quantities of produced modules it should be possible to switch to 25-30 MW/a unit sizes of the module production facilities. This in turn would lead to significant cost reductions as all existing analyses have shown. This increase of unit capacities of the production facilities is the basis for the extrapolation of module prices into the future as will be described shortly.

The shares of modules produced with respect to world regions is quite interesting. About 35% has been produced in USA, about 30% in Japan, about 20% in Europe and about 15% in other countries. In 1988 the Federal Republic of Germany has produced about 1 MW of modules which was about 3% of the world production.

The module market sales prices have decreased in the last years as is shown in Figure 1. The predicted development of prices for PV modules is shown in Figure 2. The assessment of the price development is based on analyses which either assumed definite production increases in the course of the coming years or the up-to-date price developments have been extrapolated over a certain limited time period. A number of references were used, which are generally not available and therefore can not be quoted. An exception is the analysis of Bölkow Systemtechnik [22, 23] in which future manufacturing costs of silicon modules are cited assuming production capacity units of 35 MW/a. Also a number of other references base their evaluation on the existence of similar unit sizes of module production facilities in the time period of 1995 to 2000.

The assessment of production costs of crystalline Si-modules as a function of production output of crystalline silicon is quite well founded and reproducible. The often quoted low costs for thin film technology modules are far more uncertain, because as yet only manufacturing experience for amorphous silicon exists.

3.4 Governmental subsidies

All important industrialized countries have been subsidizing R&D of photovoltaics for at least 10 years. The financial expenditures so far granted, however, are rather modest compared to subsidies of other energy options.

Germany is at present subsidizing photovoltaics with about US $55 million/a. Japan spends somewhat less on photovoltaics. In the USA the subsidies have continuously decreased in the last years and are presently about US $45 million/a. Rapidly increasing engagement is observed in Italy and Spain, while France spends only little money.

Surprisingly little is done in all countries by means of tax reductions and administrative measures to help increase PV market penetration despite the fact that significant cost reductions can only be achieved by massive increases of production outputs. Initial efforts for the introduction of renewable energies in the USA came practically to a halt when tax incentives were canceled.

3.5 Engagement of industry

Industry has strongly engaged in photovoltaics R&D especially in view of the fact that lucrative markets will only have been developed by the end of the century. As an example it should be pointed out that PV R&D in the USA has for many years to a large extent been carried out by the oil industry, whereby the expenditures sum up to well over US $2 billion, a multiple of all governmental subsidies.

3.6 Environmental impacts

PV electricity generation is characterized by the absence of radiation risks and of emissions of CO_2, air pollutants, particulates and noise. PV electrical energy production will reduce fossil energy consumption. However, some environmental effects exist and will be discussed briefly.

Land requirements for PV systems are in the range of 35-80 m^2/kW_e depending on the module efficiencies and on the geographical location with respect to solar insolation. For PV systems integrated into roofs about 8 m^2/kW_p can be achieved in Europe [14].

According to various estimates the material requirements for PV plants are in the range of 300 to 3,500 t/MW_e. This is a wide range. The lower value refers to optimized PV plant concepts which are expected in future large scale PV application. Concrete, steel and glass represent each approximately 30% of the total mass. The rest is essentially semi-conductor material (PV cells) and non iron metals. Shortages of the required materials are not envisaged except possibly for the basic material indium in case of a large scale utilization of the $CuInSe_2$-technology.

With respect to environmental impacts during manufacturing, operation and reuse of PV systems it should be emphasized that in all PV manufacturing processes potentially hazardous materials are used, which, however, are used everywhere in the chemical industry. Therefore, all legal and safety related regulations have to be obeyed. Thus, for newly to be erected PV production facilities relevant emission standards and regulations have to be prescribed [26].

The primary energy investment for the manufacturing and construction of large grid connected PV power plants using polycrystalline solar cells is approximately 9,000 kWh/kW_e [14]. For amorphous silicon: cells the value of 7,500 kWh/kW_e is quoted [14, 15]. This latter value should also be reached by using polycrystalline thin film solar cells. Further reductions of the previously quoted primary energy investments are expected in the future. Thus, according to the PV plant site energy pay back times between 1.5 to 3 years are expected [15].

4. COSTS OF PV ELECTRICITY GENERATION

It is believed that, if at all, only grid connected PV plants will contribute significantly to the overall electricity supply in the medium or long term future. Therefore, the integration of these PV plants into the already existing electrical grids and distribution systems and supply structures needs to be considered.

While conventional electricity supply by means of large central power plants exhibits considerable cost advantages it is necessary to consider and evaluate decentralized electricity supply when looking at PV. The reasons being that cost savings of large PV plants are relatively small and that the land requirements for small and medium sized PV plants pose much less problems. Moreover, roof and facade areas on houses and buildings of significant magnitude exist so that the respective technical utilization is rather simple.

Principle differences exist in the design and construction, the operational mode and in the economical evaluation of the following three model PV systems:

- Small systems (1 to 5 kW_e) on roofs of houses;
- Medium sized systems (10 to 100 kW_e) on roofs of public or industrial buildings;
- Large power plants (in the MW_e range) on open land area.

For economical evaluations it is important to realize that because of the fluctuating solar insolation and the corresponding electricity output only the actually generated electrical energy is to be evaluated economically and no credit will be given to power capacity reductions of installed plant capacity. On the other hand energy consumption from decentralized electricity generation means energy savings at costs corresponding to consumer tariffs while in case of centralized electricity generation credit will only be given equivalent to the plants electricity generating costs.

On a solely economic basis for all the above mentioned model PV systems the electricity generating costs will not be lower than those of present day power plants in the next 20 to 30 years except if unlikely and unforeseen price developments of conventional energy sources will take place.

Among the described model PV systems the medium sized PV plant (10 to 100 kW) has been identified to be the most attractive one with respect to economy and technical feasibility. These systems can be installed on flat roofs of public and industrial buildings and are coupled to the low voltage grid of these buildings and they would only supply partial load in that particular grid node. If the load characteristic is smooth enough at that node then feedback of electricity to the public grid can be avoided. The plant operator (industrial enterprise, municipal power utility) can therefore give higher monetary credit for the saved energy, namely at consumer tariffs which is higher than the lower compensation for electricity feedback to the public grid. However, usually the consumer tariffs for electricity are lower for large consumers than for small ones.

Although small systems on roofs of houses and homes are easily installed their integration into existing electricity supply structures is more problematic, because the load characteristic of a single household is fluctuating extremely and is difficult to adjust to the characteristics of solar energy supply. During the day a portion of the electrical energy would have to be fed into the grid while at times of poor solar insolation electrical energy is taken from the grid. In addition system costs for small systems are significantly higher.

Economically large PV power plants exhibit cost advantages but must however, compete with other power stations. In regions of higher insolation (solar belt) lower electricity generating costs will result. On the other hand longer electricity transmission lines might lead to cost increases.

For illustration of electricity generating costs using PV systems three different PV plants, presently in use, will be considered:

- a large power plant (10 MW_e or larger) in Germany;
- a large power plant (10 MW_e or larger) in Spain;
- a decentral medium sized power plant (10 to 100 kW_e) integrated into existing buildings in Germany.

Differences of system design and operational behaviour of these three systems are discussed in [24]. In the cost figures given differences in construction costs of the three systems have only been taken into account for the important components such as for instance the omission of costs for support structures in the case of PV system integration into existing buildings. Cost increases of decentral PV systems with smaller power ratings have generally been assumed to be 10%. The economic analysis of the considered PV systems is based on an IEA model. Details are contained in [25].

4.1 Module costs

The projected development of module costs has been discussed in section 3.3 and is the basis of the electricity generating cost estimates. The time period until 2005 is fairly well predictable, because what will happen is the industrial development of advanced modules the technology of which already exists on a laboratory scale. Cost estimates for the year 2020 are rather uncertain, because technological innovations are to be expected. A cost outlook further into the future is rather speculative. However, it can be assumed that the module costs will decrease further due to technical improvements.

4.2 Mechanical components

The costs of the mechanical components of PV systems, that are essentially those of the support structures are significant. They lie presently for larger PV systems in the range of US $110-120 per m^2 of module area. For large power plants with unit sizes of 10 MW or larger the cost are about half (US $50-60/m^2 of module area). Further cost reductions down to US $30-40/m^2 of module area are expected when lightweight components and structures will have been introduced. Increasing module efficiencies will also lower these costs because less module area (and land area) will be required.

For the medium sized PV systems integrated into buildings no costs for support structures were assumed. There will be costs for fixing devices and mounting works, which however will be compensated by the benefit of the modules in replacing other construction elements (e.g. roof tiles, facade coverings).

4.3 Electrical components

Besides the costs of modules and support structures the price of the inverter is an important cost factor. Today the inverter represents the largest electrical component of a grid connected PV system with costs of about US $1,500-1,800/kW. Cost reductions are very likely in the future due to series production and construction of larger plants. Based on the experience in the electronics industry cost reductions down to US $240-360/kW are expected. Cabling, switches and safety related equipment are conventional components and therefore the cost reduction potential is low. However, it is expected that for large PV power stations mounting of the modules will not take place at the site. Rather large module fields will be assembled in the factory and then transported to the plant site. In USA this technique has already been practiced for PV pilot plants. The cabling on the DC side is already integrated into the frames and support structures thus leading to significant reductions of mounting costs.

In the case of PV systems integrated into buildings 10% higher costs were taken into account because of the smaller PV unit sizes.

4.4 Operation and maintenance

Costs for operation and maintenance of PV systems are very low. No operating material is necessary. For maintenance only occasional cleaning of the module surfaces and monitoring of the electrical systems is required. According to US experience operational and maintenance are about US $0.5 per m^2 of module area per year.

4.5 Total electricity generation costs

Based on the previously described cost estimates total costs for future PV systems have resulted as listed in Table II. For each referenced year two PV systems have been considered, one large power plant (10 MW or larger) and one medium sized system (10 to 100 kW) integrated into a building with 10% higher size related costs.

With respect to electric energy output 2 plant sites have been considered:

a: site in the Federal Republic of Germany with 1,190 kWh insolation/m^2/a;
b: site in Spain with 2,000 kWh insolation/m^2/a.

Table II contains the electric output and investment cost figures on which the economic evaluation with respect to electricity generating costs is based as given in Table III. The economic analysis follows [16, 25]. For simplicity no taxes have been included. Moreover, the year of plant start-up is identical to that of capital investment. This is justified because construction time of PV plants is usually shorter than one year. All calculations were based on a discount rate of 6.5%. Assuming annual price increases of 2.5% results in a real discount rate of 4.0% per year. Based on the data given in Table II electricity generating costs have been calculated and are listed in Table III.

The electricity generating costs in Table III represent one of many assessments. It is obvious that there is a wide range of quoted cost data in literature due to the varying technical and economic assumptions for the time horizons of the forecasts. The electricity generating costs as given in the SUMMARY reflect a sort of mean values found in literature.

5. OUTLOOK AND RECOMMENDATIONS

PV is an environmentally advantageous way to produce electrical energy. The solar cell, a semi-conductor, is a generator in which neither internally nor in the interaction with the external environment any chemical processes take place during operation so that no emissions occur. No fuels or other operating material is required. Also there are no moving parts in a PV system; they operate without noise and need practically no maintenance.

However, there are three problem areas which must be dealt with:

- The production process of solar cells may lead to environmental impacts [26].
- In advanced thin film technologies materials are used which are known to be environmental pollutants (Cd, Se, etc.).
- Because of the low energy density of the solar radiation and due to the still low conversion efficiencies of PV modules the land requirements for PV electricity generation is rather high. This may lead to impacts on the landscape and to aesthetical effects on buildings.

These concerns are serious, however, thorough analysis and engineering they can be expected to be alleviated.

The manufacturing processes of solar cells correspond practically to those applied in the semi-conductor industry. This industrial sector fulfills all requirements of environmental protection, so that a significant increase in production capacity will technically be manageable. Because costs of emission reducing equipment are high the search for less problematic manufacturing process steps is sensible.

The use of environmentally problematic materials in PV has widely been discussed. In PV modules these materials are completely isolated from the external environment. Moreover, the quantities involved are very low. However, the reprocessing of the large amounts of modules at the end of their lifetimes is not yet solved. This problem area requires R&D in the future.

The environmental impact of PV due to considerable land requirements is a problem especially in densely populated areas. Large module areas are available if existing building structures are used. On the other hand it should be pointed out, that a large number of PV plants already exists which have been fairly well integrated into the landscape. The respective problems are not very different from those in other land consuming sectors like areas for traffic, high voltage transmission lines and other civil engineering constructions.

Table II Projected electricity outputs and investment costs of PV systems (costs per kW electrical power output)

	1995		2000		2005		2020	
	Large Plant	Med.Plant Building	Large Plant	Med.Plant Building	Large Plant	Med.Plant Building	Large Plant	Med.Plant Building
Solar Insolation, kWh/m²/a								
a: FRG	1190	1190	1190	1190	1190	1190	1190	1190
b: Spain	2000	2000	2000	2000	2000	2000	2000	2000
Electrical Power Output, kW	1	1	1	1	1	1	1	1
Lifetime, a	25	25	30	30	30	30	30	30
Module Efficiency, %	15	15	16.5	16.5	17	17	18	18
System Efficiency, %	11.4	11.4	12.5	12.5	12.9	12.9	13.7	13.7
Installed Module Power, kW_p	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
Module Area, m²	9	9	8.1	8.1	7.9	7.9	7.6	7.6
Annual Electricity Output, kWh								
a: FRG	1190	1190	1190	1190	1190	1190	1190	1190
b: Spain	2000	2000	2000	2000	2000	2000	2000	2000
Costs								
Module Costs, $/$W_p$	2.75	2.75	1.60	1.60	1.20	1.20	0.90	0.90
Total, $	3600	3600	2080	2080	1600	1600	1200	1200
Area Dependent Costs	1330	110	750	60	660	55	420	35
Power Dependent Costs	1575	1575	735	735	630	630	420	420
Indirect Costs	455	370	175	145	145	115	100	85
Total Investment Costs	6960	(5655)	3740	(3020)	3035	(2400)	2140	(1740)
+ 10 % (Small Consumer)		6220		3320		2640		1910
Operation, Maintenance	24	24	16	16	15	15	12	12

Table III Projected electricity generating costs for different PV systems in US$ per kWh

PV plant type	1995	2000	2005	2020
Large plant in FRG	0.40	0.19	0.16	0.12
Large plant in Spain	0.24	0.12	0.10	0.07
Med. plant build. integr.	0.35	0.18	0.14	0.10

Discount rate: *6.5%*
Inflation rate: *2.5%*

The biggest obstacle for the fast introduction of PV technology is the present uncertainty regarding the market development. This is the reason why at present companies do not extensively invest in new PV module production capacities. On the other hand only mass production will eventually lead to substantial price reductions and consequently resulting in a big market.

At present the market of PV modules is increasing by 16% per year. Today's technical status of PV would allow a much faster market introduction. Presently the free market forces indicate that power capacities in the gigawatt range will not be reached before the turn of the century.

Quite surprising is the fact that only in a few countries significant governmental subsidies exist to develop and introduce renewable energy sources in general and PV in particular, although their value and advantages are well known.

Governmental policy can strongly influence further development of PV. Some of the possibilities are financial support of R&D in all areas of PV (basic research, solar cells, modules, PV system equipment, etc.), compilation and dissemination of PV information (population, distributors, plumbers, users, etc.), erection of test and demonstration plants and tax incentives.

There needs to be a balance among research, development and deployment strategies. Cooperation among utilities, engineering and equipment industries, regulatory agencies and research centres is a key element.

Large scale base load deployment of solar photovoltaic technology still requires considerable development effort.

Enhanced international cooperation in R&D and technology transfer is required to facilitate implementation of the most efficient and least costly solar photovoltaic technology. Thus, the establishment of ad hoc international mechanisms for information exchange and technology transfer is needed.

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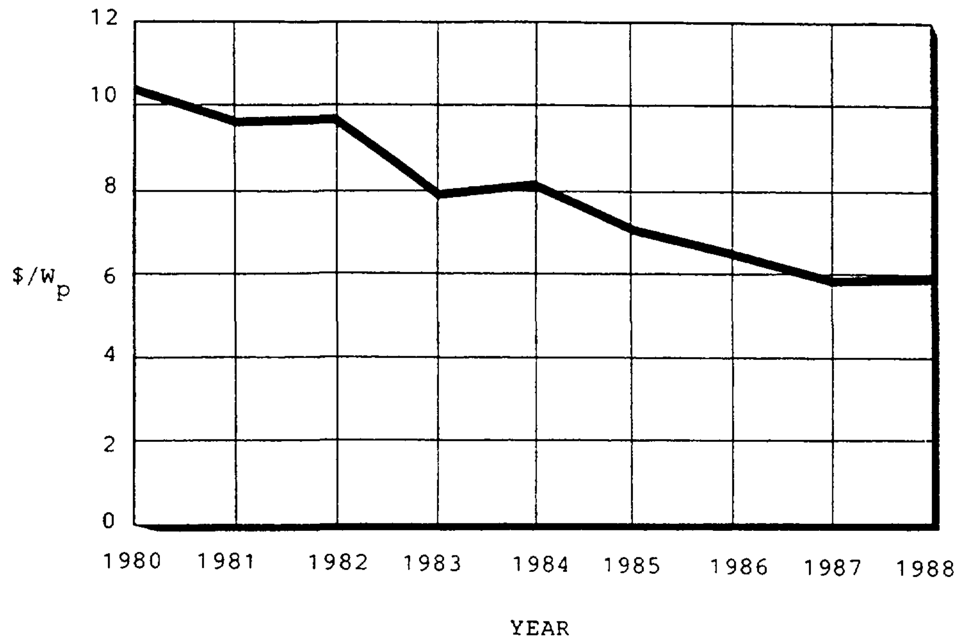

Fig 1 Development of nominal market prices for Si-Modules (average sales price)

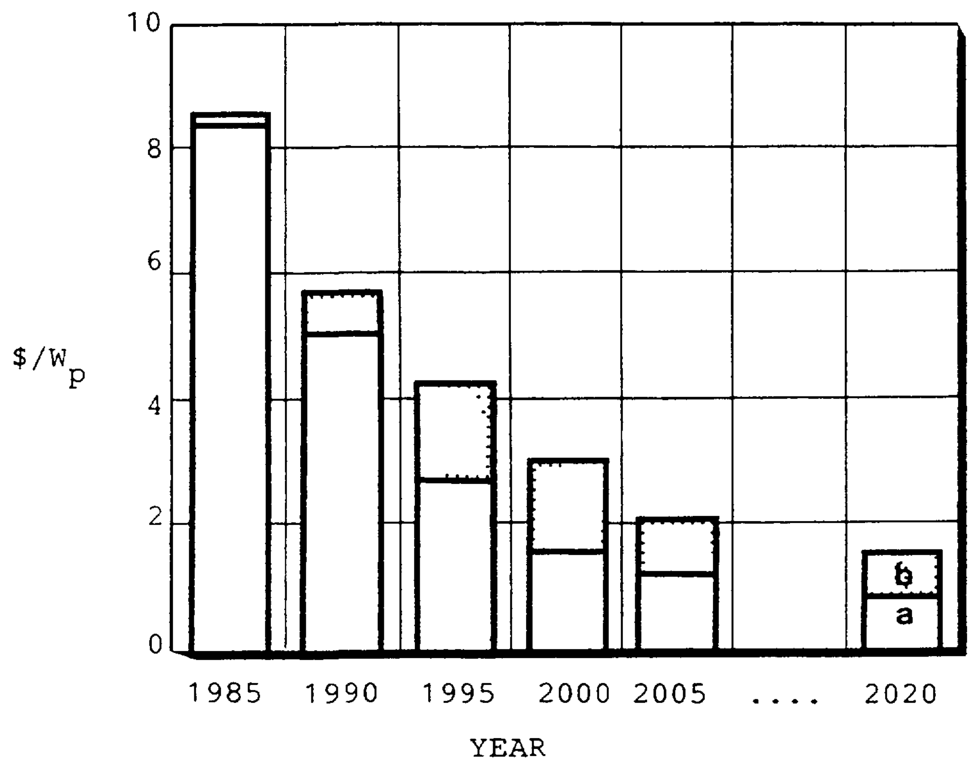

Fig. 2 Projected development of module market prices with range of uncertainty of estimates (a: lowest estimate, b range of uncertainty)

Background Papers to

COMPARATIVE ENVIRONMENTAL AND HEALTH EFFECTS OF DIFFERENT ENERGY SYSTEMS FOR ELECTRICITY GENERATION

Key Issues Paper No. 3

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COMPARATIVE TOXICOLOGY: BASES AND LIMITATIONS OF COMPARING HEALTH EFFECTS FROM LOW LEVEL EXPOSURE TO RADIATION AND CHEMICALS

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ABSTRACT: This paper describes some of the problems and fallacies in quantifying and comparing health effects from low exposures to toxic chemical and physical agents. These effects are generally too rare to be noticed in single individuals or small populations, but given the global aspects and the large fraction of the world population exposed to such exposures, the assessment of health and environmental detriment from major human activities becomes an important aspect in the choice of development options for the future.

Knowledge of the molecular and cellular effects of damaging agents and the mechanisms leading to visible health impairment is rapidly expanding. The emerging picture points to very complex webs of interactions and multistep mechanisms for important endpoints such as cancer. No unifying dose-effect concepts for different diseases in different organs are emerging. Also, practically no direct evidence of detriment to humans is to be gained for the levels of exposures from power generation in plants with state of the art emission controls, because even with very conservative assumptions, the projected health effects are too small to make epidemiological studies feasible. Due to the multitude of biologically active agents rapidly introduced into our environment and often parallel changes in exposure and life style, even unacceptably high health risk might remain hidden among the large variations in disease prevalence introduced by genetic diversity and socioeconomic factors.

Meaningful comparative risk assessments have to address the uncertainties involved and to accept that not all suspected effects can be quantified and normalized to an integral index of harm. At this stage, the assumption of low-dose linearity and the rejection of thresholds, as long as not proven, remains the method of choice to quantify and to compare health effects from most noxious agents.

1. HEALTH EFFECTS OF RADIATION AND CHEMICALS

1.1. Introduction

Low levels of toxic agents have many modes of interaction with healthy or sick organisms. Biological effects of ionizing radiation and toxic chemicals may result from the modification or destruction of cellular components such as DNA macromolecules (molecular level), or from irritation or interference with regulatory systems (cellular and organ level) resulting in reversible changes in the homeostasis of organisms. Although repair systems and redundancies at different levels, regulatory systems and immune responses etc. probably counteract countless minor insults during a human lifetime without leaving clinically relevant signs of detriment, even very low levels of toxic agents may theoretically induce morbidity or even mortality in albeit rare cases.

1.1.1. Primary effects of ionizing radiation and chemicals

The large energies released in a single alpha-decay amount to about 5 MeV (8×10^{-13} J). In comparison, the binding energy of typical chemical bonds in organic molecules amount to only 300 kJ per mol, i.e. 3 eV or 5×10^{-19} J per single bond. A single alpha particle in aqueous solution produces about 150,000 ionizations and a still larger number of excitations in the short distance it travels. Biological response to such highly localized energy depositions is complex and depends on many parameters. The following basic principles of radiation biology give the more important factors to consider [12]:

- About 70% of biological damage from low LET radiation is due to indirect action of free radicals and 30% to the direct action on the target molecule. The indirect component of radiation is strongly modified by oxygen, radioprotectors and radiosensitizers.

- Cells from different tissues vary markedly in radiosensitivity. There is no systematic difference in radiosensitivity between normal and tumour cells. At doses up to about 2 Gy, low LET radiations are relatively inefficient in killing cells. The survival curve bends with a steeper slope at higher doses.

- Radiosensitivity of cells varies according to their position in the cell cycle. In general, the sensitivity of mammalian cells to ionizing radiation is directly proportional to their rate of cell division and inversely proportional to their degree of cellular differentiation [5]. Therefore, the cellular kinetics of normal tissues and tumours are important in their responses to radiation.

- The radiosensitivity of cells to low LET radiation is greatly influenced by the presence or absence of oxygen. Most tumour contain a proportion of hypoxic cells that are radioresistant.

- The response of cells to low LET radiation can be modified by sulfhydryl compounds which scavenge free radicals (radioprotectors) and by electron affinic compounds, such as nitroimidazoles, that substitute for oxygen and sensitize hypoxic cells (radiosensitizers).

- Repair of radiation damage, the role of oxygen, the presence of hypoxic cells and the use of radioprotectors and radiosensitizers are much less important for high LET radiations, i.e. alpha radiation, than for low LET radiations.

- Heat by itself can kill cells and also inhibits the repair of cellular damage caused by ionizing radiation. Thus, hyperthermia acts in complementary fashion to increase the effectiveness of radiation damage.

Radicals formed mainly by interaction of radiation with water molecules in the cell may react with critical structures such as the DNA of the cell nucleus carrying the genetic code. The amount of primary radiation damage in biological structures per unit dose is modified by many physical and chemical agents. The most significant chemical modifier is molecular oxygen. Its ability to combine with primary free radicals formed from water to yield more damaging agents, such as the peroxyl radical, is the cause of the sensitizing effect. The oxygen enhancement ratio (OER, ratio of dose needed under anoxic and oxygenated conditions, respectively, to produce the same effect) may be considerable for low-LET radiation (up to a value of 3) and is of importance in the radiotherapy of poorly oxygenated tumours. Significant reduction of radiosensitivity occurs only at very low oxygen pressure. An oxygen pressure of 2% still sensitizes to a level which is two thirds of the value in air (21% oxygen). Since all parts of the healthy lung are well oxygenated, the full oxygen effect is to be expected in this organ. Many constituents of the cell have radical scavenging capacities and may react with radiogenic free radicals before they attack critical structures. Radioprotector molecules containing sulfhydryl groups, such as glutathione or cysteamine, are most important in the aqueous environment of the cells; other molecules, such as hydroquinones (vitamin E and K), also protect from free radicals. In addition, electron and hydrogen donors may act at a later stage and restore the native chemical structures without the involvement of enzymes by breaking up already formed labile bonds of radicals with cellular macromolecules. For an in depth treatment of molecular radiation biology, the reader has to be referred to the many excellent books devoted to this field, for example Dertinger and Jung (1969) [14], Natarajan et al. (1982) [38], Nygaard and Simic (1983) [42], Friedberg (1985) [17], and Hall (1988) [20].

If the induction of primary lesions by ionizing radiation is complex and difficult to quantify, persistent modifications brought about by chemicals are still less understood and less tractable. Many classes of toxicants can be formed based on their action. The following list of examples is not meant to be complete:

a) production of radicals
b) covalent binding to macromolecules alkylating agents
c) blocking of enzymes
d) induction of immune reactions
e) oxidation, reduction
f) acidification, alkalinization
g) interference with regulatory processes on the level of enzymes, receptors, membrane channels, etc.
h) solid state irritation

In addition to the multitude of possible mechanisms of action, chemicals are delivered through several ports of entry, e.g. lung, gastrointestinal tract, skin, and may be modified and sequestered to form substances with greatly altered carcinogenicity and solubility. Pharmacokinetic models are used to describe the fate of chemicals after uptake and to provide quantitative information on the emergence of reactive metabolites responsible for the induction of toxic effects in target tissues [34]. Considerable knowledge of the anatomy, physiology and biochemistry in the different organs of the test animal is needed to achieve this goal. Biological half-lives in different body compartments and local accumulation may be difficult to assess through all the transitions from entry to decay or release.

It is generally accepted that incorrectly or unrepaired modifications of the DNA are the main cause of radiation induced damage in cells and hence in organisms, although epigenetic effects of radiation, such as initiation of membrane lipid peroxidation [44, 45], or loss of intercellular signaling such as gap junction mediated transfer of messenger molecules [31, 35] are also possible primary causes of radiation induced cancer. Four effects can be distinguished at the cellular level (Table I). Loss of proliferative capability becomes critical only when a high proportion of the stem cells of a functional unit is affected and hence displays a steep dose/effect relationship with a threshold in the range of sieverts. More subtle changes in the genome, not interfering with proliferative capabilities but with the regulation of cellular growth, may lead to the so-called late somatic effects, i.e. cancer. Loss or alteration of crucial genetic information in gonadal cells were shown in insects and rodents to result in an elevated risk of congenital diseases in future generations.

Table I. Classification of Cellular Damage Caused by Ionizing Radiation and the Resulting effects on the Organism

Cellular change	Threshold existing	Dose > Gy	Effects on organism
Cell death	Yes	50 3 - 5	acute loss of body functions, death due to CNS (central nervous system) syndrome, vascular collapse $LD_{50/30}$ in humans
Loss of proliferative capacity	(yes)	1 0.1	loss of immune and barrier functions, death in weeks from break down of immune system, in testinal linings developmental defects during embryogenesis
Call transformation (oncogene activation)	(no)		tumours, cancer after a latency period from years to decades
Cell mutation	no		changes in the DNA of germ cells increasing the potential of genetically caused defects in the offspring

Toxic chemicals may induce all of the cellular effects of radiation. In addition, the possibility of specific binding to receptors and enzymes has the potential to induce agonist or antagonist action in almost all regulatory and metabolic pathways of an organism.

1.1.2. Quantification of risk to humans

Quantitative information on health risks from exposures to chemical and physical agents may be obtained directly from epidemiological studies of human populations. Indirect evidence is gained from the exposure of animals in controlled toxicological experiments and from in-vitro experiments with cell and tissue systems. Direct information on health effects in exposed humans is clearly preferable to animal or in in-vitro data, but for most known or suspected carcinogens there is a lack of quantitative human data. Even for well studied agents such as asbestos or ionizing radiation, the long latent periods of important endpoints such as cancer or genetic effects, poorly known exposures, and the many confounders from strongly varying life-styles and susceptibilities limit the use of human data for quantitative risk assessments outside the exposure range and socioeconomic settings of the epidemiological studies used to derive the information. Laboratory test, albeit only indirectly applicable to humans, have several advantages over epidemiological studies. They can be used to predict health hazards in advance of human exposure, total dose and dose rates are well known and can be varied over many orders of magnitude, known confounders can be controlled, and combined exposures of different agents can be performed to study synergisms. However, the translation of results from toxicological tests on animal and cell systems in the laboratory to humans poses several problems [29, 37]. Interspecies differences are erratic especially for chemicals which are modified in the body. Tests have to be conducted at high doses to induce a measurable response in reasonable time in an animal population of generally small size.

1.2. Steam cell transformation and promotion

1.2.1. Introduction

It has long been recognized that malignancies in human populations are the most important effect of exposure to ionizing radiation and many toxic chemicals. Their importance in terms of risk or detriment derives from the fact that these diseases are often lethal and that the effect may occur even at very low doses. The induction of cancer is often considered an all or nothing response, i.e. is assumed not to be graded in severity. This is an over-simplification because tumours may be graded histologically and clinically in severity, i.e. in mortality risk and swiftness of progression. Nevertheless, tumours seem to be crucially dependent on initiation events whose frequency is a function of dose. The seemingly probabilistic nature of the dose/effect relationship for malignancies has led to the use of the term 'stochastic' for effects of such type [59]. Such a notion contains an intrinsic assumption that interactions of toxic agents with biological targets relevant for the initiation of malignancies is based on chance and may occur over large ranges of doses. The postulate of a rare cellular event being at the beginning of the long response chain between the primary damage and the clinical manifestation of malignancy has important repercussions on the theoretical predictions of the shape of the dose/effect relationship. Even small increments of dose would result in a finite increased probability of cancer formation. In the case of ionizing radiation, this point is further strengthened by microdosimetric considerations which predict that doses and dose rates at the level of a cellular target, such as the DNA of a cell nucleus, are always quite high. As discussed in the preceding Section, low doses and dose rates, conceived as such on the macroscopic tissue level, mean that only a very small fraction of the critical targets is hit at all.

1.2.2. Hypotheses and models

In the scope of this treatise, only an overview of the wealth of concepts brought forward to explain the late somatic effects of exposures to carcinogenic agents can be given. This topic is covered in depth by the scientific annexes of the UNSCEAR reports (1982 [58]; 1986 [59]). For chemicals, Thorslund et al. (1987) [53] and Thorslund and Charnley (1988) [54] give overviews of biologically motivated cancer risk models.

Malignant cells are defined by certain characteristic features such as unrestrained proliferative growth, angiogenesis (the ability to attract blood supply), infiltration into neighbouring and distant tissues, and the evasion of attacks by the immune system. Such characteristics could be the result of genetic modifications, i.e. a somatic mutation, or result from epigenetic changes. Epigenetic factors, which do not lead to irreversible changes in the primary structure of the genetic code, could produce de-differentiation, activation and expression of normally suppressed genes involved in the production, binding or signalling of growth factors, inactivation of regulatory genes, or the loss of growth controlling cell-cell-interactions (gap junctions) between a transformed cell and its environment. It may well be that both genetic and epigenetic factors have to act in parallel to let a cell escape the division-restraining signals of its environment [59].

Given our incomplete understanding of the origin of cancer, it is not possible to develop quantitative predictions of the effects of harmful agents on an organism from basic principles. However, quantitative models of cancer induction based on simplified hypotheses may help in understanding the basic issues involved [63]. Most models are based on the concept of multi-stage carcinogenesis, developed first as a model for skin cancer in mice [16, 18]. The first step, initiation, is generally considered to occur in the genome of a single cell, although the involvement of a cluster of several cells cannot be excluded at this stage. Further steps towards an overt malignancy are generally assumed to be epigenetic in origin. They are often covered by the terms promotion and progression. An alternative hypothesis can be based on two initiation events, e.g. the subsequent activation of two genes from different classes of oncogenies in the same cell, or the activation of an oncogene followed or preceded by the loss or inactivation of a tumour suppressor gene. Many cellular phenomena may also be relevant in the development of a transformed cell. At the level of DNA, any change affecting the primary structure and hence its function may be of relevance for growth control. Point mutations, transpositions, deletions, translocations and transfections may all lead to the development of a malignancy. At least in the case of oncogene activation, all these genetic changes were shown to induce transformation. In addition to the direct and indirect induction of DNA lesions resulting from toxic agents, misrepair both in the so-called error-free and error-prone repair pathways, or premature DNA replication before the termination of repair processes, may lead to fixation of defects in DNA structure. The dose/effect relationships of all these possibilities are probably quite different. Somatic mutations in the classical sense show induction coefficients, for low-LET radiation, in the range of 10^{-5} to 10^{-6} Gy^{-1} per locus and cell at risk. In vitro cell transformation is even more easily induced (typical induction coefficients are in the range of 10^{-2} to 10^{-4} Gy^{-1}). This is in marked contrast to the yield of malignant tumours per irradiated cell in vivo, which is many orders of magnitude lower than anticipated from such in vitro coefficients and the number of proliferation competent stem cells present in the different tissues of large multicellular organisms like humans. A direct link to cell transformation in vitro would also predict that larger organisms with correspondingly larger pools of stem and dividing precursor cells should be more prone to cancer than small organisms. Contrary to finding more cancer in larger mammals, annual incidence rates per unit carcinogen dose seem to be inversely related to the life span, which is generally longer for larger species. Therefore, the critical lesion may consist of a very rare event such as a 'tumour-specific' chromosomal translocation [17]. It is also conceivable that the majority of the initiated cells or clones may be lost or actively destroyed at different levels of promotion which takes place during a typically long latency period prior to the appearance of a clinically recorded tumour [19].

Secondary influences, such as endogenous or exogenous growth factors, e.g. female steroid hormones in breast tissue, may increase the probability of an initiated cell passing some stages of promotion and progression, whereas other substances like the oligopeptide antipain [30] may inhibit or even reverse this process (Figure 1).

In view of the many changes in stem cells during the multistep development of cancer, it is not surprising to find wide variations in carcinogenicity in vivo. However, even in the presence of a multitude of promotional steps and host dependent influences at every level, the primary event of initiation may still be the rate limiting step, and therefore, be the decisive factor for the shape of the dose/response relationship. This contention is supported by the fact that risk coefficients for cancer induction derived from totally different exposure situations and tissue status are often found to be similar. Figure 2 is derived from data presented by Boice et al. (1979) [6] and shows such an example for female breast cancer. Dose rates were considerably different between the single, acute exposure experienced by the survivors of Hiroshima/Nagasaki and the fluoroscopy group. The therapeutic radiation doses given to the mastitis group were delivered to an inflamed breast tissue. Despite all these confounders, the three populations show similar risk coefficients. The general shape of the dose/response relationships suggests linearity. This striking finding may imply that for some forms of malignancies, the number of stages in tumour evolution may be low or that ionizing radiation is changing the probability of a late or even the last event in the multi-stage development of cancer. In the case of lung cancer, the higher risk coefficients for uranium miners starting exposure at greater ages, could be explained by an age-dependent increase in the number of precancerous cells or clones which are further promoted by ionizing radiation.

The two best studied host factors involved in the promotion of transformed cells are endocrine status and immunological surveillance. The hormonal dependence of carcinoma of the breast, ovary and thyroid is well known [13, 50, 52, 55]. Endogenous growth stimulation can be considered as a promotional factor in multi-stage cancer induction models. On the other hand, inactivation of endocrine glands should lead to the impairment of malignant growth. The low incidence of female breast cancer in the those survivors of Hiroshima/Nagasaki which had received the highest doses, is thought to be a direct effect of radiation induced impairment of hormone glands. Since functional defects occur only at elevated doses which cause pronounced cell death, any modulation of the tumorigenic response in vivo due to damage of endocrine control organs by ionizing radiation would show a higher threshold dose. The importance of immunological suppression of precancerous cells or clones formed by ionizing radiation remains to be elucidated. Studies on the influence of immunological surveillance on the induction of leukemia in mice [36] and lung cancer in rats [41] do not suggest that this host factor is decisive. On the other hand, stimulation of the immune system by exposing animals to antigens clearly increases the incidence of myeloid leukemia in preirradiated animals (Figure 3). These findings support again the contention of the importance of systemic growth stimulation of transformed cells for the emergence of overt malignancies [61].

1.2.3. Requirements for risk quantifications from primary events

In its 1986 report, the United Nations Scientific Committee on the Effects of Atomic Radiation lists the prerequisites for development of a quantitative model for the evaluation of cancer risk at low and moderate doses of ionizing radiation [56, 59]. The following points are an excerpt of the processes to be understood for a model-derived estimate. They clearly indicate that despite recent progress in our understanding, many more quantitative insights have to be gained to achieve this goal:

a) **Probability of malignant transformation of a defined target cell.** This will vary with the organ, dose, quality of radiation, local oxygen pressure, and temporal pattern of dose distribution. In this respect, the model should include theoretical concepts concerning the nature of the initiating event(s) and not be purely empirical. Mathematical formulations should be compatible with general knowledge of radiation and cancer biology;

b) **Probability of interaction at the systemic level between transformed cells or between developing clones;**

c) **Probability of cell killing, i.e. loss of proliferative capability, with dose, as non-viable cells cannot give rise to cancerous clones.** This factor depends certainly upon the tissues concerned, some of which are particularly susceptible, and upon dose, dose rate and quality of radiation and on other irradiation conditions;

d) **Effect of numerous host factors.** Among promoting factors, cell division is a good example. Enhanced proliferation can be induced by various mechanisms, including radiation-induced cell death, a phenomenon which is likely to produce a threshold-type dose response. Other factors could be the differentiation of initiated cells, immunological surveillance that suppresses development of malignant clones with antigenic characteristics foreign to the host-system, and hormonal influences;

e) **Effect of exogenous promoting agents.** These lead to more rapid appearance of tumours, to an increase in tumour yield, and perhaps also to changes in the shape of the dose/response curves, as shown by several experiments, including those on in vitro oncogenic transformation [21, 30].

2. WHAT DO WE KNOW ABOUT THE EFFECTS OF LOW-LEVEL EXPOSURES?

2.1. Dose/effect relationships in carcinogenesis

2.1.1. Introduction

The spectrum of health effects from exposure to chemical or physical agents depends on many variables. Due to a multitude of biologically active substances in our environment and often parallel changes in exposure and life style, even unacceptably high health risk may remain hidden in the large variations in disease prevalence introduced by genetic diversity and socioeconomic factors. Even if epidemiological studies show effects correlated with an exposure, it may be difficult to prove causality. For small effects, a causal relation, i.e. a chain of events dominating the relationship between dose and effect, may be explored in an *in vitro* test system such as the DNA strand break assay (Figures 5 and 6) or in an epidemiological study of a population with a quantifiable exposure to the agent of interest. The development of appropriate dose/effect relationships extending to low doses typical for chronic exposure situation is the central feature of any environmental risk assessment. Contrary to the risks in the moderate to high dose region which can be explored in epidemiological studies, effects from low-level exposures are often not more than guesses based on indirect evidence. For exposures below the threshold for acute injuries, late effects such as cancer and genetic defects in the offspring are the most significant health risk. For these endpoints, the clinically identifiable health detriment, i.e. the effect, generally occurs decades after the time of exposure. An additional problem of great importance encountered in the study of malignancies arises from the high incidence of cancers due to major confounders such as smoking or eating and drinking habits. Radiation-induced lung cancer may serve as an example. Since the type of cancers caused by ionizing radiation or chemical exposures are the same as those occurring spontaneously or due to smoking, the cause of an individual lung cancer cannot be linked explicitly to environmental exposures. Histological studies gave only weak correlations of histological types of lung cancer with age at diagnosis, total dose and smoking history [1, 3, 27, 28, 51]. Therefore, even for an individual with a known history of elevated exposure to ^{222}radon and its daughter products who develops lung cancer, it is only possible to estimate what portion of the individual's total calculated risk is due to radiation exposure and what portion comes from other causes such as smoking. The U.S. National Institute of Health recently released radioepidemiological tables based on the concept of probability of causation [40], that are intended to serve as guide-lines for legal disputes over worker compensations. The major obstacle posed by long latency periods and the statistical noise generated by the spontaneously and life-style induced fractions of the health detriment are somewhat counterbalanced by the relative ease of dose calculations and the additivity of consecutive exposures to ionizing radiation.

Because doses at the work place or in the environment are much lower than exposures known to produce measurable risks in human populations directly, the risk estimate for low-dose ionizing radiation is derived from dose-response functions [3, 8, 40]. Most of the mathematical models in use today are based solely on total dose. The fact that this is a crude simplification of a complex system with many additional variables should always be remembered. The general equation for radiation-induced cancer from Barendsen (1978) [2] shows the many complexities involved in modeling risk:

$$Y = (a_1 + a_2 D + a_3 D^2) \cdot e^{-b_1 D - b_2 D^2} \cdot F_{immun}(D) \cdot F_{hormon}(D) \cdot F_{stem}(D)$$

In this formula, a_1, a_2 and a_3 are the parameters for spontaneous, linear and quadratic terms of the dose dependent probability of tumour induction, respectively. b_1 and b_2 are the linear and quadratic dose dependent terms for cell killing which lead to a reduction of the number of cells at risk. The other factors denote the dose dependent influence of immune function, hormonal responses and tissue repopulation. Although the extent of primary damage due to ionizing radiation is less variable per unit dose than for example the effect of a procarcinogen which may need metabolic activation and transport through membrane barriers, even the health detriment of low doses of ionizing radiation is still dependent on many poorly known variables. The number of division-competent stem cells affected, the presence of other mitotic stimuli [61], and the levels of endogenous hormones which may act as promoters of transformed cells in the target tissue, e.g. the female breast, are examples of variables to consider.

2.1.2. An example: radiation quality and biological effectiveness

Beside the total dose, various other factors, such as speciation of the agent and dose rate are of importance for the shape of the dose/response curve. Here, the quality of radiation is used to show the many problems and fallacies encountered in assessing detriment. Ionizing radiation is often classified into low-LET and high-LET to describe biological effects since the quality of the radiation, i.e. the linear energy transfer which is a measure of ionization density along the track, is a major determinant of fractionation and protraction effects. Under environmental conditions, the former class is represented by beta particles and gamma/X-rays, the latter by alpha particles and neutrons. In the following, the molecular and microdosimetric theories to understand and quantify the large differences in the biological effectiveness per unit dose for different radiation qualities are outlined.

At the microscopic level, beta- and gamma-radiations produce similar ionization patterns. Gamma photon energy is first transferred to one or few electrons which then deposit energy in the tissue by producing ionizations and excitations along its path, i.e. similar to an electron resulting from a beta-decay. A large difference exists however in the macroscopic depth distribution of dose or penetration. External gamma- and x-rays reach much deeper into the body than beta-particles. This is the result of the relatively low probability of interaction for the photon in soft tissue. The ionization density along the electron path is in the range of 25 to 100 mm^{-1}. Given the fact that most of the radicals formed by the interaction of radiation with water, which is the major constituent of cells, travel only few nanometers [14], it is generally assumed that low to moderate doses of low-LET radiation are less efficient in producing highly localized damage required for adjacent breaks on both strands of a DNA double helix leading to a double strand break. DNA single strand breaks are repaired efficiently and generally error-free, while DNA double strand breaks are critical for cell survival and chromosome modification because of their much slower repair and the much greater risk of misrepair, deletions or translocations. This is probably strongly influenced by the fact that correct repair of double strand breaks requires redundant information sitting on the homologous chromosomes present in diploid or polyploid cells. For single strand breaks, the second undisturbed strand of the same DNA double helix provides the information directly. The mechanisms and enzyme complexes involved double strand break repair are very complex and correspondingly slow and error-prone [25, 62]. Figure 7 shows the spatial relationship between the critical structure of DNA and the ionization density at the beginning of the electron path from a ^{14}carbon decay [11]. Recoil and transmutation, i.e. conversion of the carbon atom into a nitrogen atom at the place of radioactive decay, only produces one single strand break or a base loss, leading to a temporary strand break during repair. Therefore, in view of the large average distances between consecutive ionizations, the probability of a beta-particle producing a double strand break along the path or even at the beginning of the track is quite small. Only the last few ionizations of an electron are clustered more densely, leading to a higher potential for complex local damage. This has considerable implications on the kinetics of repair and on the effects of fractionation and protraction. Earlier hypotheses assumed that low-LET radiation mainly produce the critical double strand breaks by the interaction of two independent particles. Since the probability of two electron tracks interacting with the same DNA segment is proportional to the square of the dose, quadratic dose/effect relationships would result from such model. Given the fast repair of single strand breaks in mammalian cells, a quadratic dose rate/effect relationship should be seen. These notions were not confirmed by microdosimetric considerations which indicate very low probabilities of hitting a target with a radius of only few nanometers by two independent electrons. Below 1 to 2 Gy the chance for such an event is practically zero. However the hypothesis cannot be refuted totally because it is possible that lesions quite far apart may interfere with each others repair, thus creating the possibility for an important quadratic contribution in the dose/effect equation for low LET radiation.

An upward concave dose/response relationship is observed for sparsely-ionizing radiation in many animal experiments. In addition, a sparing effect of dose fractionation and protraction is generally seen for low-LET radiation. For lung adenocarcinomas in BALB/c female mice and for lung adenomas in RF mice, a quadratic term compatible with two track kinetics was only found at quite high dose rates, far above the environmental exposure rates [57, 66]. New epidemiological findings based on the reassessment of the dosimetry and — more important — a longer follow-up of the survivors in Hiroshima and Nagasaki suggest that at least for female breast and lung cancer the quadratic term in the dose/effect equation is less important than primarily thought.

Alpha-radiation with a typical path length in soft tissue of about 50 mm for an initial particle energy of 5 MeV clearly belongs to the high LET-radiation. The corresponding ionization density along the track is in the range of 2,000 mm^{-1} or 2 nm^{-1} (Figure 8). If compared to critical structures in the cell nucleus such as the DNA double helix, it becomes clear that a single alpha-particle may cause almost any molecular endpoint considered as the starting point of transformation. This means that the formation of double strand breaks or even of two or three adjacent double strand breaks which may be needed for chromosome rearrangements, e.g. translocation of an oncogene to an active part of the genome, will follow single track kinetics, giving a linear dose/effect relationship. In addition, the energy deposition patterns would not predict any sparing effects from the lowering of the dose rate, from fractionation or protraction, because dose and dose rate at the level of the cell nucleus is barely affected by this shift. If a cell nucleus is hit by an alpha particle, the energy deposited in the fraction of a second amounts to about 0.4 Gy or 8 Sv averaged over the nucleus. Alpha-doses well below the value of 0.4 Gy lead to an extremely inhomogeneous distribution of dose at the level of the cell nuclei. A high-LET dose of 0.4 mGy (0.0004 Gy) per year to an organ means that only a tiny fraction of less than 0.001 of the cells are hit once per year with a maximal dose of 0.4 Gy and a dose rate of many kilograys per second. For low-LET radiation, the maximal energy for a cell nucleus hit once is considerably lower, i.e. in the range of 3 mGy or 3 mSv.

The prediction of linearity for high LET effects based on microdosimetric considerations is also supported by results from animal experiments. In contrast to gamma-, X- and beta-radiation, the incidence of tumours shows little dependence on dose protraction and fractionation for high-LET radiation [59]. Contrary to the sparing effect found in general with low-LET radiation, low alpha or neutron dose rates or fractionation lead in some test systems to an enhancement of effects as compared to a single high dose rate exposure. In C3H 10T1/2 cells, Hill and coworkers found an increase in the transformation frequency of up to a factor of 9 by reducing the neutron dose rate from 0.38 $Gymin^{-1}$ to 0.86 $mGymin^{-1}$ [22, 23]. Cell survival was not significantly affected by the shift in the dose rate. No convincing explanation of this phenomenon has yet been offered. Hypotheses brought forward include the induction of error-prone repair or the facilitation of the expression of 'sub-effective transformation damage' (Han et al., 1984). Most of the epidemiological data from miners exposed to high-LET radiation from ^{222}radon and its decay products suggest a linear or even downward concave dose/effect relationship for low and intermediate doses [24, 27]. On the other hand, an increase in the latency period with lower dose would result in an upward concave relationship especially for exposures received late in life.

An important aspect of LET and radiation quality in the assessment of low level effects is the temporal and spacial distribution of radiation events in critical tissues. Based on microdosimetric data , a low dose of 10 mGy (1 rad) received over a time period of 10 years, will translate into only a few events per cell nucleus. For low LET radiation, 10 mGy produce about 7 electron tracks per cell nucleus; the average time period between two events in the same cell would be more than one year. For high LET radiation, a macroscopic dose of 10 mGy does not even translate into one alpha track per cell nucleus in the affected tissue. Only a small probability of being hit in the range of 4% for an 8 mm diameter volume results. Dose rates at the level of the cell nucleus for low exposures of any LET remain always extremely high (above a MGy per second). Such microdosimetric considerations suggest linearity for genetic changes occurring in single cells. Since alpha tracks passing through a cell nucleus induce cell death (loss of proliferative capacity) with a high probability, localized stimulation of stem cells may occur even at low doses. Correlations of such epigenetic effects with dose or dose rate are not well known. Figures 9 and 10 give computer-simulated numbers of hits for six cell nuclei encountering environmental low LET radiation, and for six stem cells below/in the bronchial epithelium of an uranium miner, respectively. From the indoor exposure for the life periods before and after the mining experience at the limit for occupational exposure, it is seen that the majority of the stem cells in the most critically exposed parts of the lung will not even encounter one alpha track from indoor radon during a human lifetime of 80 years. The probability of being hit from a radon daughter exposure of 160 mSv H_{eff} (2 mSv per annum) is less than 50 percent [9].

Microdosimetric concepts do not only help in the quantification of doses and dose rates in critical compartments, they may also help to understand epigenetic effects. Since the local cellular effects from alpha tracks are acute and non-stochastic, cell death and effects on cell proliferation may occur even at low doses. Figure 10 shows that bronchial stem cell nuclei exposed at the occupational limit encounter less than one hit per year but typically several during an employment period of more than one decade. Under the assumption that many cells hit by an alpha track lose their capability to divide, an exposure at the occupational limit already leads to profound changes in the repopulation kinetics of lung stem cells. This is an epigenetic aspect of alpha radiation which may have its influence on the dose effect relationship at low exposures, i.e. may lead to a deviation from linearity.

2.1.3. Considerations specific to chemical carcinogens

Besides the difficulties stemming from the wide range of possible modes of action and targets, assessments of chemicals have also to consider pharmacokinetics. In addition to the listing on page 8, the following steps have to be addressed [67]:

- Entry of the toxicant into extracellular fluids and transport around the body
- Transport through cell membranes (receptors, active transport)
- Receptors and transport within the cell
- Reactions producing the active carcinogens, e.g. cytochrome P-450 enzyme activation reactions as well as deactivation reactions
- Transport of the carcinogen through the cell, across cell membranes, through extracellular fluids, through target tissue cell membranes
- Receptors within the target cells and transport throughout such cells

These levels correspond to the information provided by microdosimetry in the case of ionizing radiation. The newly developed methods to measure DNA-adducts from very small exposures to chemical carcinogens [32], theoretically allows one to start assessing damage from chemicals at this point. The further steps outlined by Zeise et al. (1987) [67] cover the requirements given by UNSCEAR on page 8. The difference in wording is a vivid indication of one of the problems in comparative risk assessments:

- Action on the DNA and other cellular components
- Repair mechanisms and their failure
- Cellular division rates, which may be affected by the cytotoxicity of the chemical, and mechanisms which act to prevent subsequent repair of damage
- Other necessary effects before a cancerous cell is generated
- Immune system responses of the whole organism to the altered cells or products of such cells
- Cell to cell communication
- Growth rates of damaged cells

The authors state that this list is not considered to be complete, and that many of the processes can contribute to a nonlinear dose/effect relationship.

For historical reasons, and because there are clearly more steps involved in the assessment of chemicals, many more dose/effect models were brought forward in the field of chemical toxicology than have been for radiotoxicology. In addition to the linear, linear-quadratic and quadratic correlations used for low-level effects from radiation, a multitude of non-linear models are described in the literature for chemical toxicity. Schaeffer (1981) postulated a threshold model derived from thermodynamic ideas [49]. Much earlier, Mantel and Bryan (1961) suggested to adapt the probit formula, which is the standard model for acute toxic effects, to also describe cancer induction by chemicals [33]. A model which allows one to fit almost all continuous data sets, is the multihit model [48]. Here, it is assumed that a number of hits, (k), is needed to fully transform a cell. Assuming further that hit probabilities are proportional to dose, that no specific sequence is required, and that all hits have equal probabilities, Poisson distributions result. For low doses (d), the response is proportional to d^k. Values of k below 1 result in superlinear relationships, values much higher than 1 produce sublinear, threshold-like curves. With our knowledge on carcinogenesis rapidly increasing, quite complicated models to quantitate steps such as those outlined in Figure 1 emerged. Such multistage models [63] include one or several transitions per cell, one or several cells needed for tumor development, importance of order of transition, and different transition probabilities. From what we know about the many different changes involved in cancers from different stem cells, it is not surprising that no unifying concept has emerged from these modelling efforts.

2.1.4. The proper use of dose/effect-relationships

Despite many similarities, there are also basic differences between chemical carcinogens and ionizing radiation. Important classes of chemical carcinogens lead to primary damage which is quite similar to that from ionizing radiation. They include substances known to bind covalently to DNA, e.g. alkylating agents. Other chemicals might bind to DNA and produce radicals (bleomycin) or prevent the scavenging of endogenously produced radicals (poisoning of enzymes by heavy metals). To stress these similarities, the term 'radiomimetic drug' was coined for bleomycin. Even for those chemicals, an important difference in the low exposure range exists. At the cellular level, very low exposures to chemicals will lead to only a few lesions per unit time and cell nucleus. However, as described in the preceding section on microdosimetry, very low doses of ionizing radiation will still lead to local clusters of lesions along the particle tracks.

For many toxic chemicals, the primary biological effect is not caused by a single molecule producing a change in the genome. Other targets such as proteins or lipids might be more important. Growth signals or circuits of the nervous system might be affected by changes in the fluidity of lipid membranes. It may be postulated that such a change needs the presence of several molecules of toxicant per growth receptor or ion channel. The dependence of the formation of the active complex on the toxicant concentration is then highly nonlinear, i.e. the model predicts an apparent threshold. In such a case, the linearity assumption entails considerable conservatism. On the other hand, for procarcinogens that have to be transformed to the toxic substance by cellular enzymes, the saturation of the involved enzyme complex at low concentrations leads to an underestimation of the concentration of the active toxicant at low concentration when the experiments were performed with precarcinogen concentrations above the saturation level of the activating system.

As a conclusion, it may be fair to say that the many diverse modes of action of toxic chemicals, pharmacokinetic considerations and the possibility of enzymatic transformations, suggest a much larger range of dose/effect-relationships for toxicants than for ionizing radiation. But even with nonlinear relationships being experimentally prevalent for chemical carcinogens, and theoretical reasoning also leading to postulation of nonlinearity, most of the time it remains questionably whether and to what extent such a nonlinear response occurs in humans [67]. Therefore, the necessity to assume linearity remains for most environmentally important pollutants.

In a situation where the shape of the dose/effect relationship is not known sufficiently, a proper risk assessment has to include a discussion of the uncertainties involved. This is particularly true when addressing the public's need for quantification to be simple and clear. Statistical uncertainties of epidemiological data and of results from bioassays, belief and constraints imposed by the professional background, as well as the position and statute of individuals and committees, may influence judgements in many ways. Zeise et al. (1987) emphasize that the essence of risk is uncertainty [67]. They conclude, therefore, that to ignore uncertainty is to incorrectly describe risk. This proper approach leads often to a situation where the emphasis on the large confidence intervals makes further assessments and comparisons practically worthless. Fortunately, in the real world at least some partial solution to the problem exist. Upper bounds of risk, even when very high per unit dose because of large uncertainties, may still be irrelevant when compared to other risks of the activity under consideration. If trading off one specific risk against another, some or most of the uncertainties may become irrelevant on a relative scale. In comparative risk assessments, it is crucial to use similar assumptions for all substances assessed. Naturally occuring substances or agents are often attributed a best estimate of risk, agents from industrial activities a conservative estimate, whereas many xenobiotic substances for which no tests are available might wrongly be considered safe. Different detection limits and ease of measurement, as well as our partial knowledge, have often been major confounders in comparative risk assessments.

3. RELATIVE AND ABSOLUTE RISK

Even when assuming a no-threshold, linear dose/effect relationship for health effects from low-level environmental exposures, the question of interdependence of different risks, synergisms, remains. From what was said earlier about the molecular mechanisms of cancer induction, it is quite clear that different agents can act on many of the single steps given in Figure 1. When we assume that the spontaneous incidence of a disease is also the result of one or several cells which underwent those modification, then the different exposures and the natural aging process would act in common. This means that their interactions would tend to be rather multiplicative than additive. The results from many experimental systems and epidemiological data sustain this notion. The combined effects of smoking and occupational asbestos exposure or smoking and occupational radon exposure on lung cancer mortality are clearly higher than independent, additive risks would suggest. New data from the survivors of Hiroshima and Nagasaki also suggest that for solid tumours, ionizing radiation seems to increase the spontaneous, highly age dependent non-radiogenic cancer risk by a constant factor per unit dose.

3.1. Relative risk models

The most widely used measure of association between an exposure characteristic and the resulting disease is the relative risk (RR). **A model based on a relative risk projection implies that the risk from a given exposure is dependent on the spontaneous risk, i.e. is**

modifying the spontaneous incidence rate by a factor. The following equations are used to describe the relative and the excess relative risk (eRR):

$$RR = \frac{\textit{Incidence rate of the disease in exposed group}}{\textit{Incidence rate of the disease in nonexpected group}}$$

$$eRR = \frac{\textit{Excess incidence rate of disease in exposed group}}{\textit{Incidence rate of the disease in nonexposed group}} = RR - 1$$

It is assumed that an excess in the age-specific lung cancer rate is both proportional to the exposure and to the normal cancer rate in the unexposed control group. Lung cancer is strongly age dependent, the rate increasing at about the 4.5^{th} and 5^{th} power of age for non-smokers and smokers, respectively [15]. Therefore, a relative risk projection will give a much higher absolute annual excess lung cancer risk per unit exposure for a person of the age of sixty than for a twenty year old. The same holds true for a smoker in comparison with a non-smoker of the same age.

In the scope of this treatise, dealing mainly with environmental exposures, two simplifying assumptions can be made. If the exposure rate and the relative excess cancer risk coefficient are constants, i.e. not changing with time or age, the following equation for the total age-specific cancer rate emerges:

$$d(t) = d_0(t) \cdot [1 + r \cdot E \cdot (t - g)]$$

$d(t)$	age-specific cancer mortality rate
$d_0(t)$	spontaneous cancer mortality rate in the unexposed individual
t	age
r	relative risk coefficient (assumed constant over age)
E	annual exposure to a carcinogen
g	latency period (time between exposure and onset of elevated risk) (assumed to be constant)

Using radon-induced lung cancer as an example, the proportional hazard model can also be applied to smokers. This would imply a multiplicative or synergistic influence of tobacco smoke on the lung cancer mortality rate. Such a relationship is often suggested by epidemiological studies with a short to moderate follow-up period. However, an update of the lung cancer risk assessment of the U.S. uranium miners suggests the presence of a considerable additive component for the extended follow-up of populations at risk [24]. Assuming the following equation for smokers not exposed to ionizing radiation:

$$d_{0,s}(t) = d_{0,ns}(t) \cdot [1 + S_s(t)]$$

$d_{0,s}(t)$, $d_{0,ns}(t)$	age-specific lung cancer mortality rate for smokers and non-smokers, respectively
$S_s(t)$	smoking factor characterizing the synergistic influence of smoking.

The total age-specific lung cancer mortality rate for smokers in a relative risk model is given by:

$$d_s(t) = d_{0,ns}(t) \times (1 + S_s(t)) \times [1 + r \cdot E(\; - g)]$$

spontaneous *smoking* *radon*

The three terms *'spontaneous'*, *'smoking'* and *'radon'* denote the corresponding contributions to the total, age-specific lung cancer mortality rate. For chronic smokers who start smoking at the age of 20 years and continue smoking at the same rate until the end of their life, the smoking factor S_s amounts to about 0.7 per cigarette/day [64, 65]. For non-smokers the second term is one or near to one if possible detrimental health effects from passive smoking are taken into account here.

In recent publications, relative risk models are clearly favoured over absolute models for radiation induced carcinogenesis in man. Although they tend to be in better agreement with the epidemiological data, the large influence of age makes them more prone to large errors for time intervals not covered by the epidemiological follow-up. Under the assumption of a fixed age-independent relative risk coefficient for the life span remaining after the onset of expression of the cancer risk (age at exposure plus latency period), many fatalities will occur late in life in a period not yet covered very well in epidemiological studies.

3.2. Absolute risk models

An absolute excess risk model assumes that different pathways leading to the appearance of cancer act independently of each other. Therefore no temporal correlation with the spontaneous or tobacco-dependent lung cancer rates, which are both highly age-dependent, increasing over a considerable part of the human life span with the 4.5th and 5th power of age, respectively, is sought. Although the prevalence of such models in the past was mainly a matter of methods in use at that time, a biological base could also be given. A cancer induction mechanism with only one rate-limiting step, such as a mutational event in a single oncogene, may well serve as the basic theory for the independence of radiogenic, chemical or endogenous cancer induction in man.

For a single, acute exposure to a carcinogen, an absolute excess risk model will predict that, after a latency period of several years, a constant excess rate of lung cancer will be discernible in the population for the remaining lifetime or for a fixed expression period. For a linear dose/effect relationship, the model can be described by the following equation:

$$d_e(t_e, t) = a(t_e) \cdot E(t_e)$$

$$\text{for } t > t_0 \text{ and } t > t_e + t$$

d_e	annual excess lung cancer rate
t_e , t	age at exposure, age, respectively
a	absolute risk coefficient

E exposure at time t_e
t latency period
t_0 40 years (accounts for the fact that lung cancer below the age of 40 is very rare)

For a chronic exposure situation such as the exposure to radon daughters in the indoor environment, the annual excess lung cancer rate is given by integrating exposures multiplied with age-specific absolute risk coefficients. Assuming an age-averaged risk factor (a_e) and stable exposure conditions, the excess lung cancer rate is given by:

$$d_e(t) = a_e \cdot E_a \cdot (t - t)$$

for $t > 40$ years

a_e age-averaged absolute risk coefficient
E_a annual exposure in chronic exposure situations

For ^{222}radon in the indoor environment, ICRP gives an age-averaged risk coefficient (a_e) of 1.1×10^{-11} $year^{-1} \cdot (Bq/m^3 \cdot h)^{-1}$ [27].

From the models on radon-induced lung cancer adopted by major committees in the eighties, only the NCRP 78 model [39] is based on absolute risk, i.e. additive rather than multiplicative relationship between excess and baseline risk. The radiation induced excess risk is assumed to be independent of smoking and sex. The risk at a given age is only determined by exposure level and time since exposure. There is a latent period of 5 years with no excess risk; later the lung cancer risk from radon exponentially decreases. In addition it is assumed that there is no excess lung cancer risk before the age of 40. The NCRP 78 model results in the following equation:

$$d_e(t_e, t, E, S) = d_0(t, S) + 10^{-5} \cdot a(t)\ {}^{a}(t - t_e) \cdot E$$

$$a(t) = 1 \quad \text{if } t > 40$$
$$= 0 \quad \text{if } t < 40$$

and

$${}^{a}(t - t_e) = e^{-(t-te) \cdot ln(2)/20} \quad \text{if } t - t_e > 5$$
$$= 0 \quad \text{if } t - t_e < 5$$

d_e annual radiogenic incidence lung cancer rate
$d_0(t,S)$ baseline rate for a person of age t with smoking history S
t_e , t age at exposure, age, respectively
a absolute risk coefficient
E exposure at time t_e

The decrease in the absolute risk coefficient with time since exposure is based on a biological model which assumes that stem cells in the bronchial epithelium, which are transformed by the radon daughter exposure, have themselves a half-life for survival or proliferation competence, i.e. are cleared from the lung with time. The maximal excess lung cancer risk occurs 5 years after cessation of exposure. From then on, the radiogenic risk decreases with age which is in contrast to the non-radiogenic risk, which increases dramatically with age until age 70.

3.3. Fitting the data, the BEIR IV model

Both the relative and the absolute excess risk models for radiation induced lung cancer can be fitted to available epidemiological data. However, prediction of risk for age groups poorly represented in the human populations studied for radiogenic lung cancer may vary considerably between the different models. Since recent developments hint at both a relative and an, albeit smaller, absolute excess risk component [4, 24, 47], a pure relative risk model with a life-long expression period may substantially overestimate the lung cancer mortality risk from ionizing radiation for age segments with high spontaneous lung cancer mortality, i.e. older age groups. The resulting misperception is further increased because of the decreasing individual and societal detriment with increasing age at diagnosis of the lung cancer. In many recent approaches, a cancer occurring at old age is weighted less than a fatal cancer early in life. This is done by normalizing the impact of the health detriment on an index of harm, e.g. on a scale of loss of life expectancy [26]. The first problem can be alleviated by introducing correcting elements into the models. To get a better fit of the relative excess model, the relative excess risk coefficient for exposure below the age of 20 is taken to be 3 times larger than for adults, thus correcting the very low risk prediction of this model for younger age groups [27]. A limitation of the expression period or a decrease of the relative excess risk coefficient after a certain time since exposure for radiogenic lung cancer mortality could also be envisaged in view of the latest findings [4, 24]. In the absolute model, which tends to overestimate risk at lower ages and to underestimate at higher ages, the validity of the model may be restricted to people above the age of 40, and a longer latency period may be assumed [39].

The BEIR IV (1988) report [4] contains a careful and sophisticated approach to fit a model to epidemiological data from miner populations (see also Chapter VII and Table VII.1). In its analyses, the committee focused on the following potential risk factors:

- cumulative exposure
- duration of exposure
- age at which risk is being evaluated
- age at first exposure
- time since cessation of exposure
- time since different parts of exposure
- effects of smoking (only in the Colorado Plateau uranium miner cohort)

The BEIR IV committee used a relative risk model, i.e. the ratio of the excess risk to the background age-specific risk, to examine how the age-specific risk depends on the above variables. The report states that this was done by making a cross-classification of numbers of lung-cancer deaths and person-years at risk, by categories of these variables, and then fitting models to the rates given by the ratio of deaths to person-years in such a tabular cross-classification. The regression models were fitted with a Poisson probability model for the number of deaths in each cell of the table, where the expected value was taken as the product of the person-years at risk for the cell and a cancer rate given by the parametric model. The starting point of the analysis was the following general mathematical form of the relative risk:

$$d(a) = d_0(a)[1 + \{b \cdot g(u) \cdot W\}]$$

$d(a)$	lung-cancer mortality rate for a given age and calendar period
$d_0(a)$	background or baseline risk of the lung-cancer mortality in the population
W	cumulative exposure in WLM at 5 years before age a
b	basic slope of the dose-response relation
$g(u)$	modifying effects of variables (u) other than cumulative exposure

This general form assumes that exposures have no substantial effect on risk of lung-cancer mortality for the first 5 years, and that risk increases linearly with cumulative dose. The BEIR IV committee also felt that for prolonged exposures, early exposures may contribute less to the risk later in life and tried to fit a time since exposure (TSE) model, which contains two time intervals prior to a specified age at risk. The 2 intervals are the 5^{th} to the 10^{th} to the 14^{th} year (5 - 15), and 15 and more years. It was further determined by the committee that effects of age at risk on the relative risk coefficient had to be taken into account. The analyses of four different cohorts showed quite consistent results with a decline in excess relative risk with both age at risk evaluation and time since exposure. To account for the decrease of relative risk dependent of age, three age categories of less than 55, 55 - 64, and 65 years of age or more were formed. The BEIR IV committee finally arrived at the following numerical values for the general equation:

$$d(a) = d_0(a)[1 + 0.025g(a)\ (W_1 + 0.5W_2)]$$

$d_0(a)$	age-specific background lung-cancer mortality rate
$g(a)$	1.2 for age a less than 55 years
	1.0 for age a between 55-64 years
	0.4 for age a being 65 years or more
W_1	dose in WLM incurred between 5 and 15 years before risk evaluation
W_2	dose in WLM incurred 15 years or more before risk evaluation.

The decreasing values of $g(a)$ with age are a reflection of the increase of real risk with age, as seen in the epidemiological studies, which is clearly less than predicted from the relative risk model with constant risk coefficient. The risk for the miner cohorts studied has both an absolute and a relative component. Whereas in the BEIR III report (1980) [3], an absolute model was fitted to the data by introducing absolute risk coefficients increasing with age, the new approach reduces the relative risk coefficients with age. The abrupt changes of risk at the boundaries of the age intervals are artefacts of the simple step function. The actual pattern is thought to be gradual [4].

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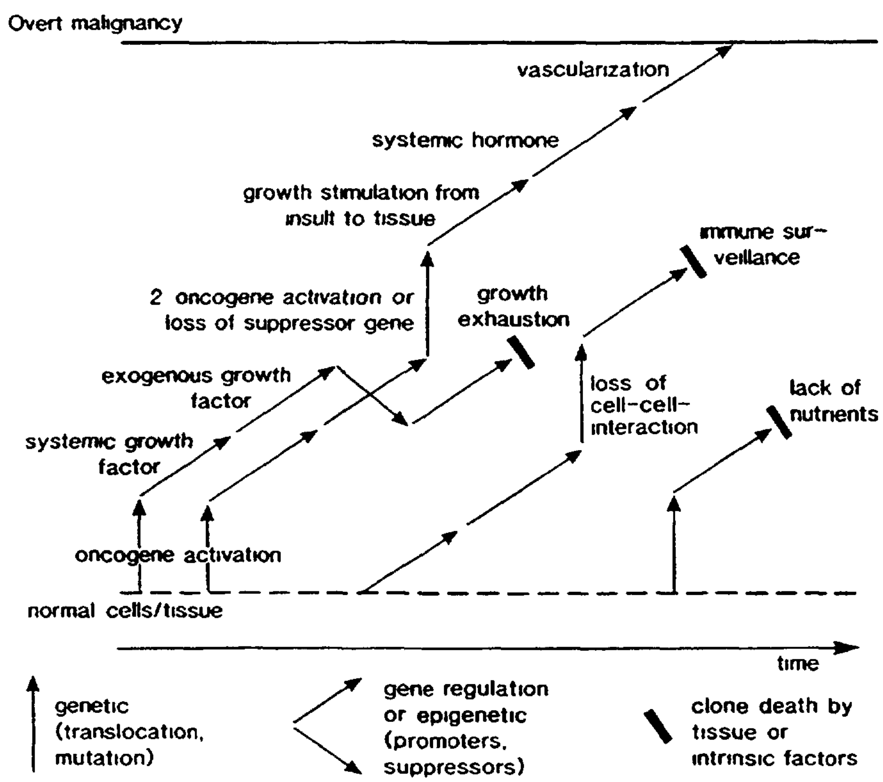

Fig. 1 A model for the multi-stage development of an overt malignancy. Some of the factors are purely hypothetical. The listing of factors is not meant to be complete.

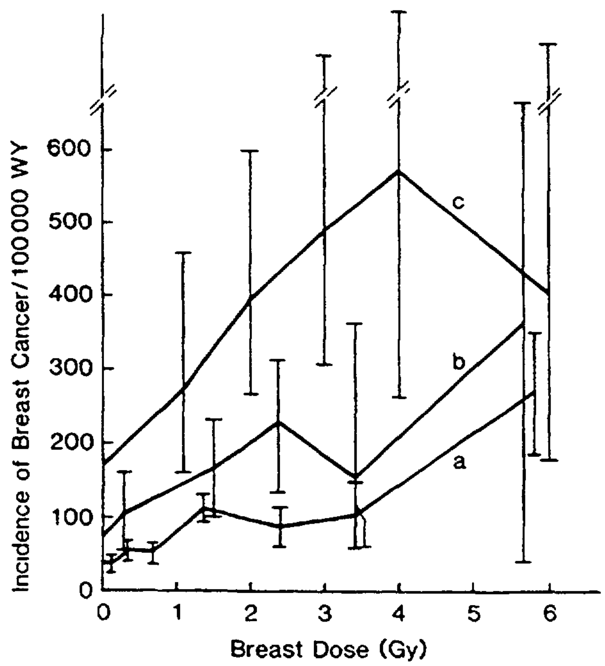

Fig. 2 Dose responses for radiation induced breast cancer in different human populations [6].

a) atomic bomb survivors (corrected by a factor of 1.5 for DS86 dose changes [46])

b) Massachusetts fluoroscopy

c) mastitis patients

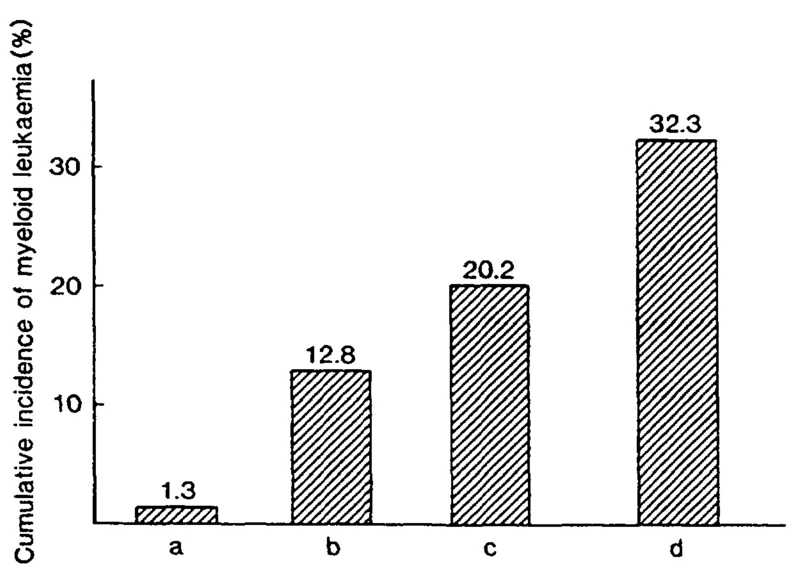

Fig. 3 Dependence of cumulative incidence of myeloid leukemia in irradiated Rf mice on the bacteriological status. Dose was 300 R (about 3 Gy) and the animals were followed up to the age of 2 years [60, 61].

a) mice maintained permanently germ-free
b) germ-free mice which were conventionalized after irradiation
c) germ-free mice which were microbially shocked after irradiation
d) conventionally maintained mice

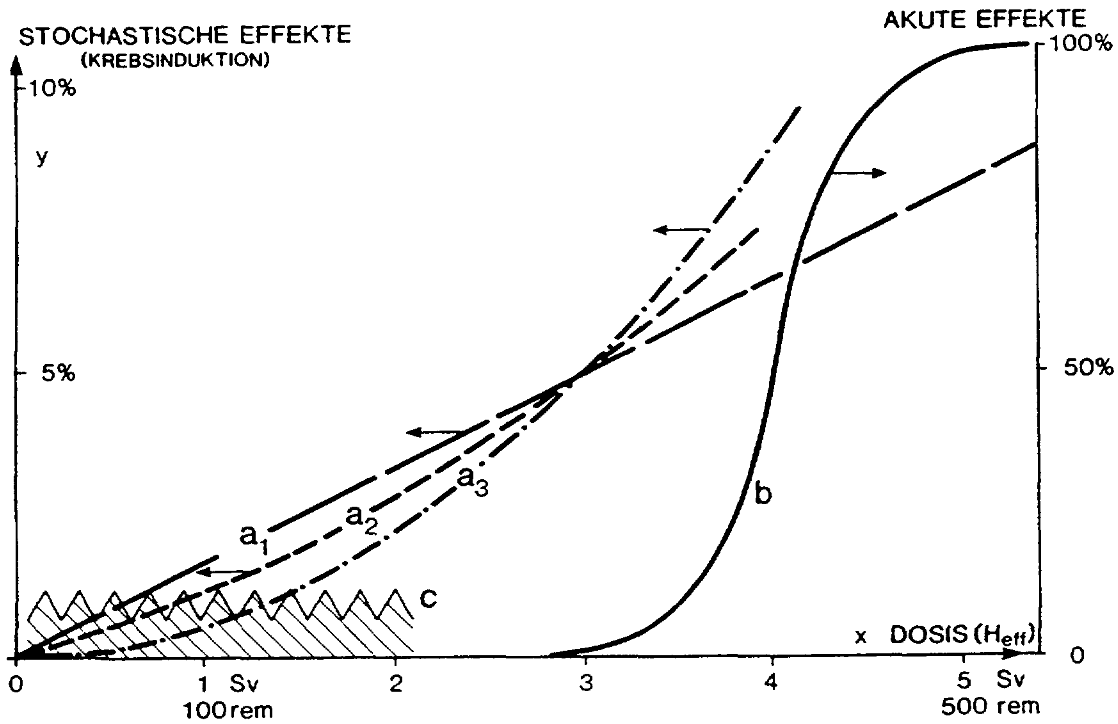

Fig. 4 Dose/effect relationship for different radiation-induced health detriments [10].

a) Stochastic: cancer induction, genetic effects

a_1) linear (genetic effects, carcinogenesis from alpha, conservative for beta and gamma?)

$y = ax$

a_2) linear quadratic (carcinogenesis for low-LET radiation?)

$y = ax + bx^2$

a_3) quadratic (carcinogenesis for low-LET radiation?)

$y = ax^2$

b) Nonstochastic: acute effect with threshold and steep sigmoidal dose-effect response

c) Interference from other causes of cancer

Dose: a) total accumulated dose (may be much more than acute lethal dose without showing any nonstochastic effects if spread over a long time period)

b) acute dose

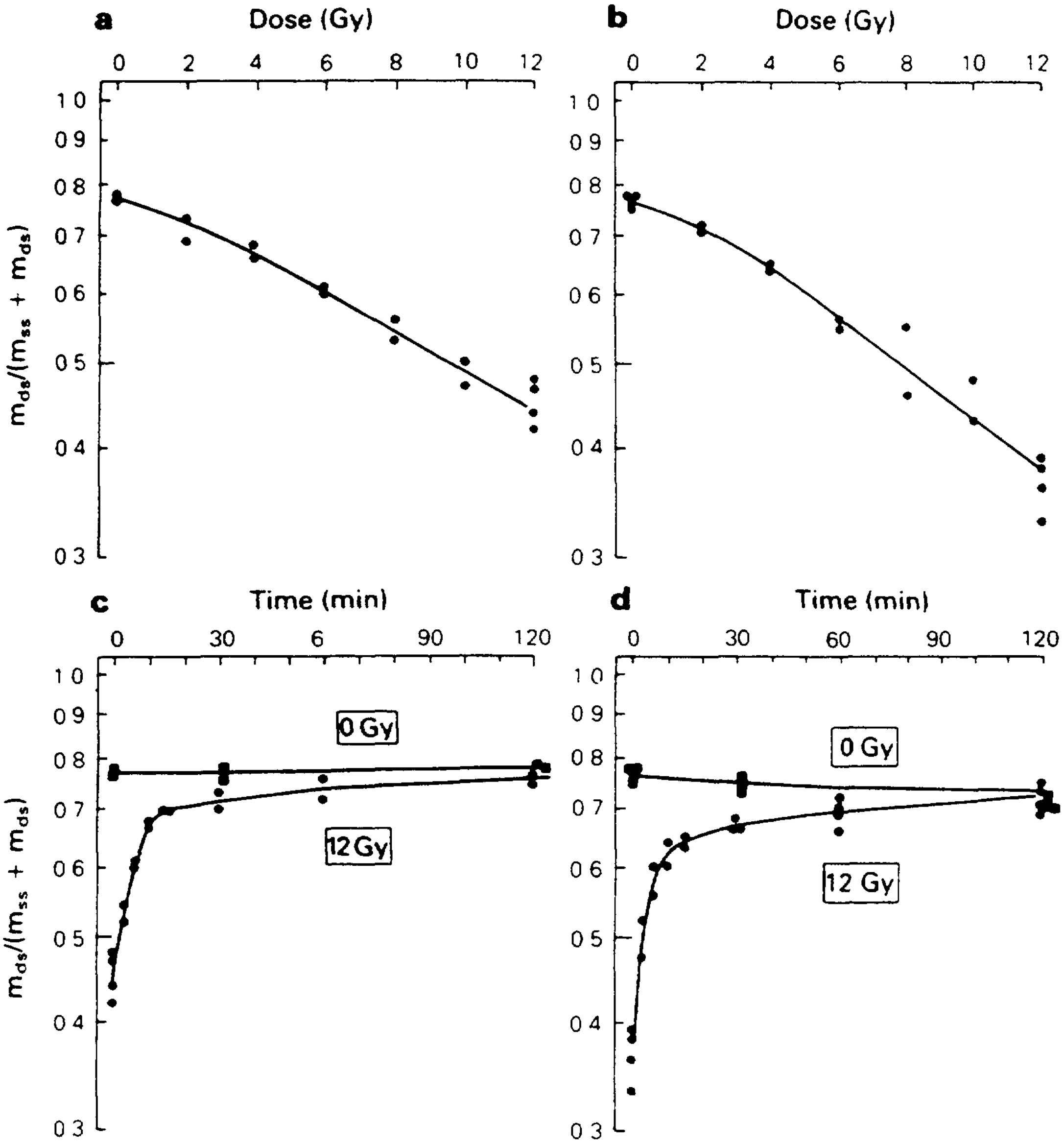

Fig. 5 Dose dependent accumulation and repair of DNA strand breaks in tissue culture cells measured indirectly as DNA strand separation in alkaline solution:

Dose response curves of DNA strand separation in X-irradiated cells, (a) myoblasts, and (b) myotubes. Change in the fraction of double-stranded DNA ($m_{ds}/(m_{ss} + m_{ds})$) as a function of repair incubation time in growth medium for (c) myoblasts and (d) myotubes [43].

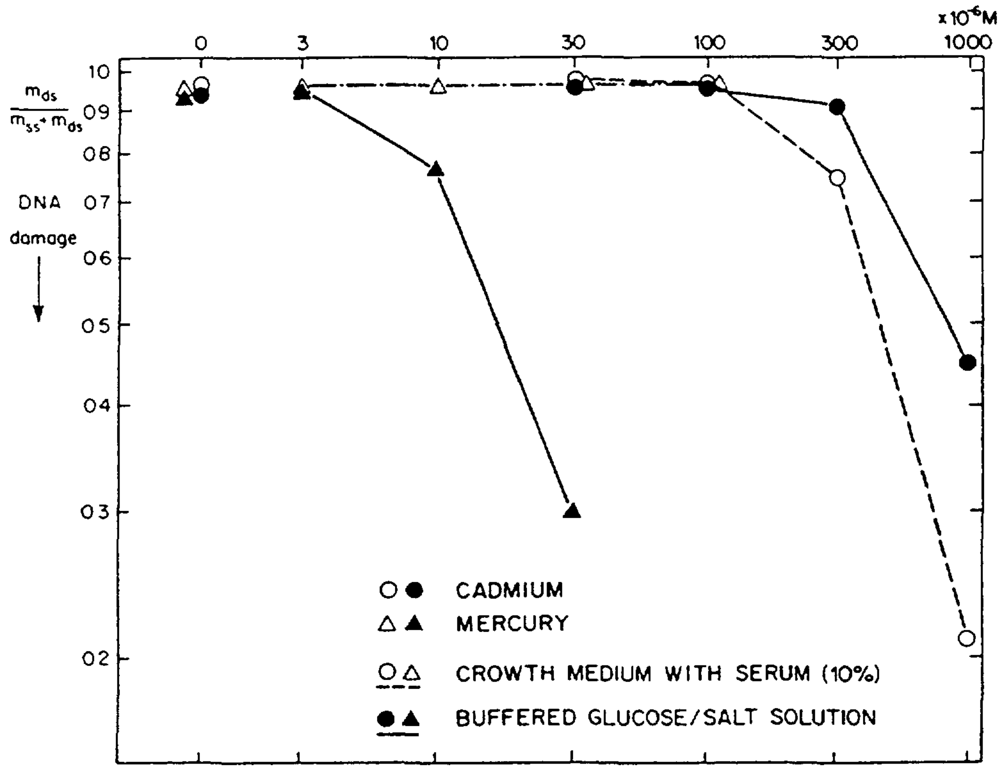

Fig. 6 Example of dose dependent accumulation of DNA strand breaks in tissue culture cells measured indirectly as DNA strand separation in alkaline solution:

V79 cells after 4 hour incubation at 37 °C with heavy metals. The results show a strong dependence on cell culture medium and concentration of cadmium and mercury [7].

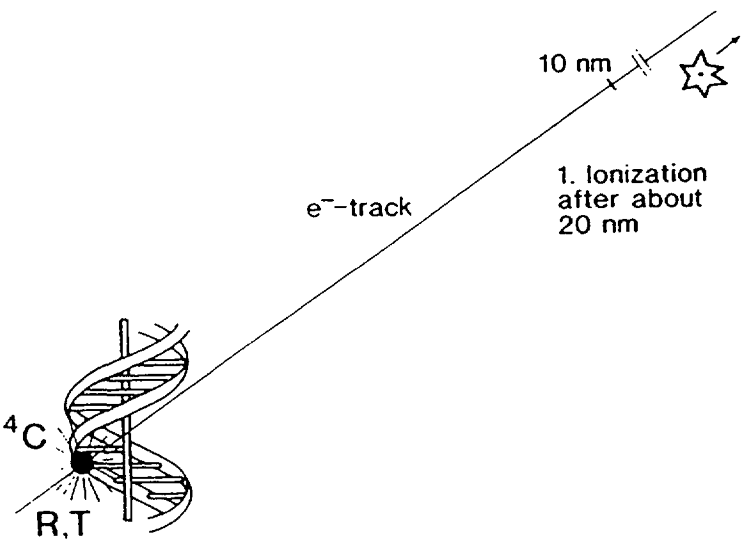

Fig. 7 Dimensions of the DNA double helix in comparison with the interaction density at the beginning of the electron track resulting from a ^{14}C decay ($E_{Average}$ about 50 keV).

The local effects due to transmutation, T (i.e. conversion of a carbon into a nitrogen atom), and recoil, R, lead to one DNA single strand break [11].

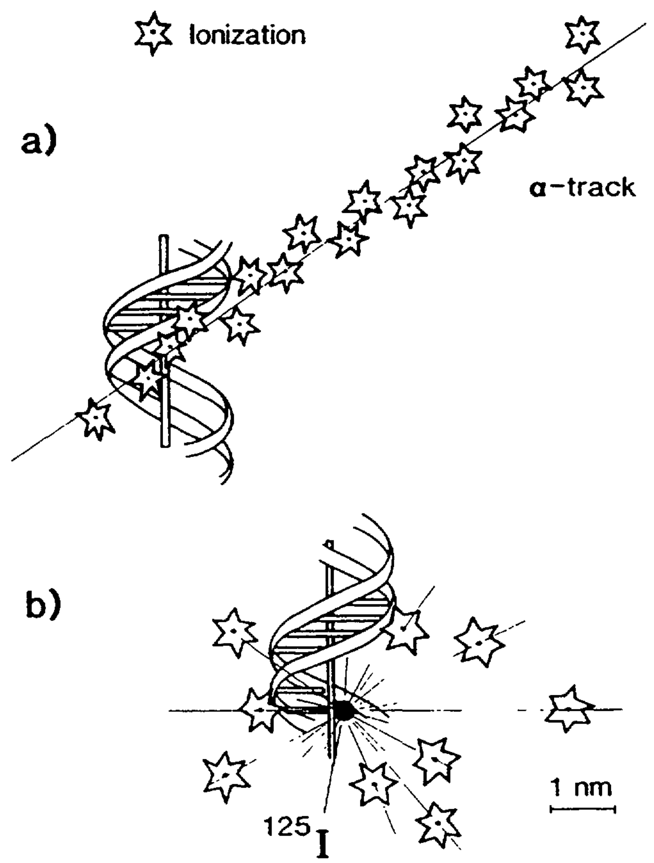

Fig. 8 Dimensions of the DNA double helix in comparison with the ionization densities along an alpha track (a) and at the site of a ^{125}I decay producing an Auger cascade with about 20 low energy electrons (b) [11].

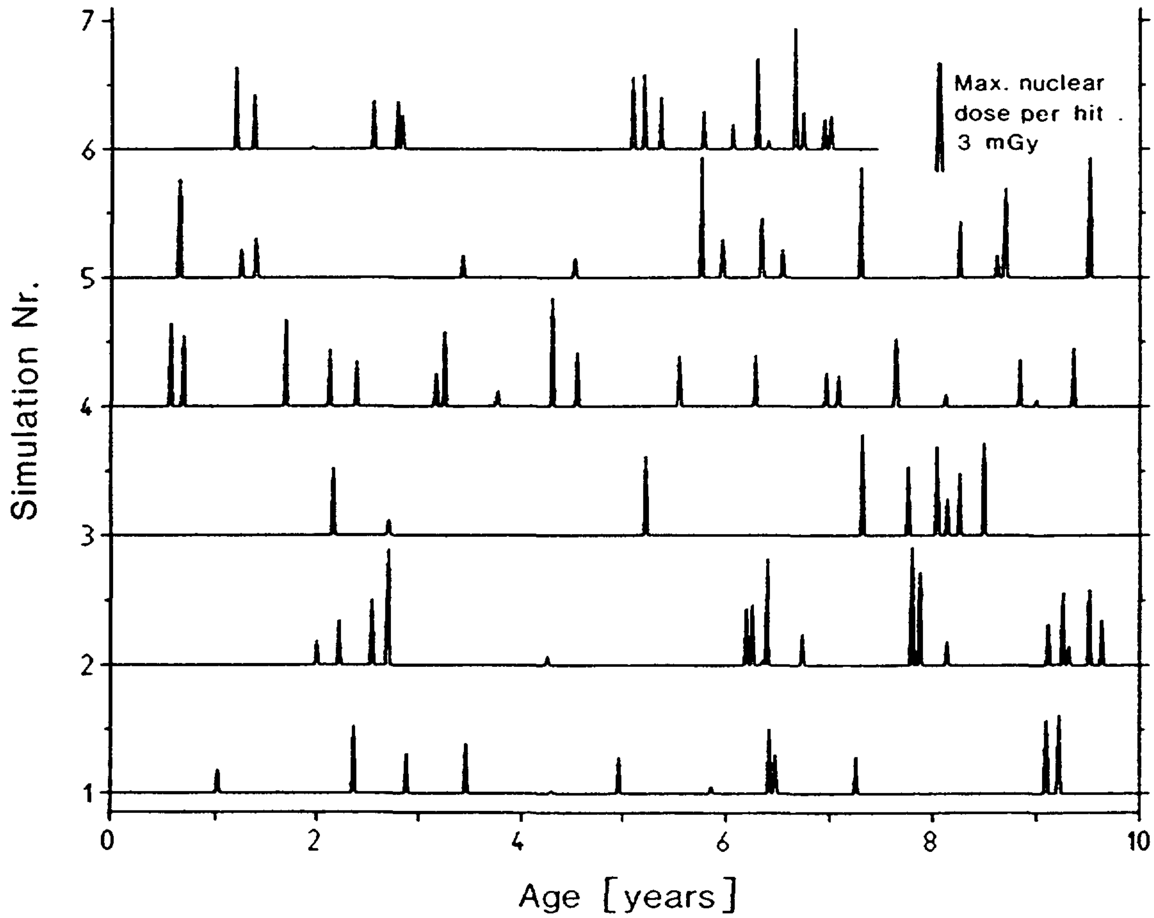

Fig. 9 Computer simulated hits for 6 cell nuclei over a period of 10 years from environmental beta/gamma irradiation. Macroscopic annual doses of 2 mGy and maximal nuclear doses of 3 mGy per hit are assumed.

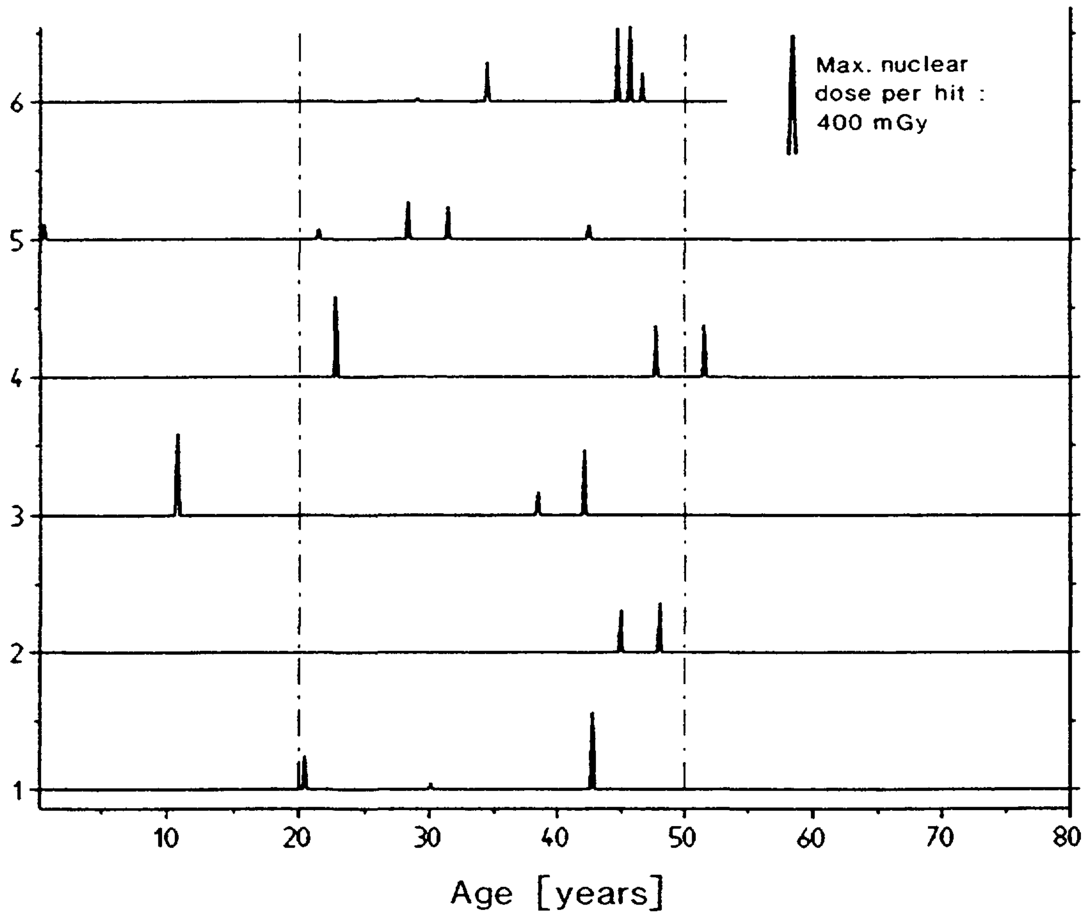

Fig. 10 Computer simulated hits for 6 bronchial cell nuclei over a lifetime from environmental and occupational radiation exposure.

Model assumptions: 1 mGy environmental radon exposure to the lung per year (corresponding to about 2.5 mSv H_{eff}), 20 mGy per year (50 mSv H_{eff}) during occupational exposure between the age of 20 to 50, maximal nuclear dose of 400 mGy per hit.

CRITICAL LOADS AND CRITICAL LEVELS FOR THE EFFECTS OF SULPHUR AND NITROGEN COMPOUNDS

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ABSTRACT: Estimates of the man-induced global annual sulphur flux for the mid-1980s are put at about 93 (±14) million tonnes sulphur, of which some 80 million tonnes sulphur were emitted in the form of SO_2. Of this, 75 per cent results from the combustion of fuel, mainly fossil fuel. Sulphur dioxide may be transformed chemically in the atmosphere and transported hundreds of kilometres before being deposited where harmful effects may result. Thus, solely national efforts to reduce the harmful effects of such deposition by abating emissions are unlikely to be very effective. Transboundary pollution phenomena must be taken into account, and it has proven to be the impetus for evolving regional co-ordinated abatement strategies for SO_2 and NO_x emissions.

The paper presents the approach that is increasingly being adopted as basis for abatement strategies, and discusses the applications of such an approach in the European context.

The approach is one in which the acid buffering capacity and rate of a site are being determined. This is employed, along with other site features, such as the sensitivity if living systems to acid conditions, to set a critical load value for the ecosystem. A similar approach is being presented concerning the direct effects of air pollutant concentrations, such as SO_2 or NO_x, by setting critical levels.

The critical load and critical level concept does provide a relatively firmly based scientific yardstick by which to judge progress towards pollution minimization. Their use as a basis for target load establishment also provides a practical means of effecting progress in pollution abatement agreements that incorporate a cost effective approach.

1. INTRODUCTION

Estimates of the man-induced global annual sulphur flux for the mid-1980s are put at about 93 (±14) million tonnes S, of which some 80 million tonnes S were emitted in the form of SO_2 [8]. Of this, 75 per cent results from the combustion of fuel, mainly fossil fuel. Although the man-induced sulphur represents only about one-third of the total global sulphur flux, because over 90 per cent occurs in the northern hemisphere, there are areas here (particularly in Central Europe) where man-induced sulphur deposition far exceeds the deposition from natural sources.

The direct effects of sulphur dioxide tend to be local and spatially related to the emission source. However, sulphur dioxide may be transformed chemically in the atmosphere and transported hundreds of kilometres before being deposited where harmful effects may result, far distant from the source. Thus, solely national efforts to reduce the harmful effects of such deposition by abating emissions are unlikely to be very effective. Transboundary pollution phenomena must be taken into account and it has proved to be the impetus for evolving regional co-ordinated abatement strategies for SO_2 and NO_x emissions.

The United Nations Economic Commission for Europe (UN-ECE) Convention on Long Range Transboundary Air Pollution (LRTAP) came into existence in 1979 and into force in 1983. An 'SO_2 Protocol' stipulated specific agreements on the reduction of national annual sulphur emissions, or their transboundary fluxes, by 1993. Nineteen countries signed the Protocol in 1985 in Helsinki, agreeing to at least a 30 per cent reduction over 1980 emissions. In November, 1988, the 'NO_x Protocol' was agreed in Sofia. In addition, EC countries have agreed a directive on emissions from large combustion plants that should result in an overall reduction of 60 per cent in SO_2 emissions by 2003 and reductions of around 30 per cent of NO_x by 1998, within the Community.

However, as understanding of the basic ecological effects of acid depositions improves, it is becoming apparent that emission abatement to achieve the necessary deposition reductions, in some areas, will be called for that are considerably in excess of those envisaged by the existing international agreements. To take one example, it has been estimated that a reduction of approximately 75 per cent in S deposition (from approximately 80 keq km^{-2} yr^{-1} to approximately 20 keq km^{-2} yr^{-1}) would be required to return certain Scottish lochs to their non-acidified status [3]. Such a situation also applies to many areas in Europe. In fact, the approach that is increasingly being adopted is one in which the acid buffering capacity and rate, of a site, are being determined. This is employed, along with other site features, such as the sensitivity of living systems to acid conditions, to set a **critical load** value for acidic depositions below which damage to the ecosystem structure or function is unlikely to occur. A similar approach has been adopted to the direct effects of air pollutant concentrations, such as SO_2 or NO_x, by setting **critical levels**.

This critical load/level approach has come into prominence as more stringent abatement levels are sought. Where there is uneven access to emission control technologies and ability to meet the costs of overall abatement, concentration on a cost-effective strategy involving the attainment of deposition reductions to meet targets, based on scientific criteria, becomes an attractive and practical method of progress. Deposition reduction targets can be set to allow for the variation in the level of deposition that has been determined will not cause damage to ecosystems. This may be set against using an overall percentage reduction, irrespective of spatial variations in sensitivity.

Critical load estimates are not simple to obtain. A critical load is 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' [65]. Essentially the concept is a dose-response or exposure-effect one. Hence, all kinds of questions arise:

- What constitutes a realistic measure of 'dose' over a period of time and should 'chronic' and 'acute' doses be represented differently?
- How are doses in multiple-pollutant systems dealt with?
- What represents a satisfactory measure of response in complicated systems and how is the 'harmful effects' threshold recognized particularly where variability masks clear effects?
- Should alterations of both **structure** and **function** be taken into account and, if so, how would this allow for new equilibria situations?

Questions of a different nature also arise from a critical loads approach. These chiefly concern the logic of not polluting 'up to' a critical load if this threshold can be accurately determined; alternatively, there is the question of why it should not be desirable to use the best available technology (BAT) to abate emissions below critical load values where such technology exists. There are answers, of a sort, to both such sets of questions but, as critical loads and critical levels estimates increasingly indicate the need for more stringent levels of abatement, the debate becomes less and less relevant to practice. Not only is it evident that, in many areas, BAT will need to be applied to attain critical load values but also, even with all BAT applied, in certain areas, reaching critical loads will not be a feasible goal. Nevertheless, the critical load and critical level concept does provide a relatively firmly-based scientific yardstick by which to judge progress towards pollution minimization. Their use as a basis for target load establishment also provides a practical means of effecting progress in pollution abatement agreements that incorporate a cost-effective approach.

2. THE CRITICAL LOAD-CRITICAL LEVEL CONCEPT

The critical load concept applied to ecosystems assumes a threshold response to acid depositions in terms of the onset of harmful effects. Below the threshold it is postulated that acidic depositions will not give rise to deleterious effects on animal, plant and other life and that these will only begin to occur once the critical load is exceeded. Critical loads for certain elements, such as nitrogen, will have to take account of the possibility of the existence of limitation of supply and also nutrient imbalances induced by accumulation as deposition proceeds. The critical load is thus a site specific, 'pollutant' and ecosystem specific value. It will depend upon a combination of site factors which influence the sensitivity of the site to depositions and hence the response of the biota.

Gaseous pollutant concentration standards for direct effects on plants and vegetation have also been suggested and are known as critical levels [82]. These are also based on a threshold response assumption, the critical level being the concentration of such substances as SO_2, O_3 and NO_2 respectively above which damage is caused.

The critical load concept used for acidic depositions owes its origin to the 'target loading' concept proposed by Canadian scientists, in relation to the deposition of sulphates to aquatic systems, during the transboundary pollution control negotiations with the USA [9, 61]. An upper limit of deposition was proposed to safeguard all but the most sensitive of lake ecosystems. The concept was further developed in Scandinavia and the term 'critical load' was used [63, 64]. Critical load values were suggested for a range of aquatic and terrestrial sites in Scandinavia that would take account of both sulphur and nitrogen depositions. A critical load was defined as [63, 64], 'the highest load that will not cause chemical changes leading to long-term harmful effects on the most sensitive ecological systems'. The phrase 'long-term' was taken to mean 50 years or more [63].

3. CRITICAL LOAD CRITERIA

Critical loads applied to acidic depositions rely on the assumption that there are rate dependent processes in ecosystems which act as sinks for acids and are able to fully neutralize the acidic deposition. It is assumed that there is enough capacity to neutralize acidic depositions in the long term. These rate dependent processes include the rate of weathering of soil minerals in the catchment and microbial reduction of sulphate and nitrate. It is postulated that if the total input of acidic substances to the ecosystem is less than the rate at which the acids are neutralized then there will be no net acidification of the system and hence no harmful effects will occur.

It has not yet been possible to directly relate all the major facets of biotic response to acidic deposition (dose). The basis of the critical load concept is generally the response of biologically relevant chemical characteristics. One approach is to require that no decrease in base saturation occurs so that all acidic inputs are consumed by processes such as weathering and since this will guard against changes in soil chemistry there will be no deleterious response by the biota. Other threshold values of soil chemical parameters also may be set. Among the most commonly used for terrestrial systems are pH and alkalinity, calcium: aluminium ratio and the change in concentration of NO_3^- in soil solution. Sverdrup and Warfvinge [74] set critical loads to safeguard coniferous forest ecosystems by assuming a pH > 4.0-4.3 should be maintained in the O, A and upper B horizons and a soil solution alkalinity of >0.03 meq l^{-1} at the base of the B horizon. For lakes and streams runoff from the soil should have an alkalinity of at least 0.05 meq l^{-1} which equates with pH 6.0. In aquatic systems the water pH affecting fish response is a commonly used variable but base cation concentration and the toxicity of biologically active aluminium species have also been included.

Minns, Elder and Moore [60] have attempted to take the criteria closer to actual biological responses. The basis for surface waters' critical loads assessment is the loss of one fish species from amongst the twelve most commonly occurring species in the region. It is suggested that, although a single species loss is not a viable threshold to choose when dealing with other taxa such as invertebrates, it is possible to select a loss of a proportion of the various taxa. Inclusion of these (such as molluscs or leeches) will lead to more stringent critical loads being set.

4. LIMITATIONS OF THE CRITICAL LOAD CONCEPT

The critical load concept provides a way of setting a deposition standard based on environmental effects and criteria. There are, however, limitations to this approach and these relate to dose considerations, considerations relating to response and identification of the target units, and also to operational disadvantages of the concept.

Dose-related limitations include difficulties of integrating chronic dosages over time to produce single value estimates and decisions related to using criteria of that sort rather than 'peak' or acute, episodic dose criteria. A second difficulty arises due to the non-comparability, in dose terms, between a system that is already undergoing acidification and one that is in a relatively pristine condition but may be at risk; a similar critical load value might be applied to both. Furthermore, the use of critical loads, so far, assumes that the trajectory of recovery, in relation to dose, is the same as degradation under initial increasing acidification. This assumption ignores hysteresis effects which may occur. For example, buffering mechanisms involving adsorption and desorption are known to show hysteresis as are biological systems when density changes occur during colonization and perturbation at different rates. A third difficulty relates to the complicating effect, on straightforward threshold dose recognition, of changes in other pollutants or interacting factors. Indeed, the most satisfactory way of representing the dose-response relationship of a mixture of pollutants may be in terms of a linear no threshold model [11].

From the response point of view, it may be difficult or impossible to detect with certainty a threshold of damage. It is to be expected that where relatively simple 'pollutant' substances contain essential elements, a threshold model is, a priori, the most likely relationship. However, uncertainty boundaries in the dose response relationship might equally well accommodate both a threshold or a linear no threshold model response.

In addition, the many elements of an ecosystem may react differently to variation in pollutant level or rate of deposition. Fish are often taken as the target organism in aquatic ecosystems [60]; however, there are more sensitive biotic elements that will decline before fish are affected [24]. The integration of ecosystem response in relation to particular critical loads or levels is extremely difficult, particularly as both structural (species diversity, species number, food web features, population density, standing crop) and functional (rate of photosynthesis, rate of respiration, maintenance efficiency, nutrient turnover) attributes, at least theoretically, should be taken into account. There is also a further response consideration that is fundamental to the critical load concept. The concept is a steady state, static variable attempting to describe a response of a dynamic system. Ecosystems may acidify naturally; depositions of acids are accelerating this process. Therefore, the critical load referring to the existing equilibrium state is also taken to refer to the ecosystem at a changed equilibrium state, sometime in the future. The problem of whether critical load values should allow for ecosystem adjustment to some future equilibrium condition is partially dealt with by suggesting a time frame within which the critical load estimate should guard against adverse changes [63, 64]. This is important as the time lag between the delivery of a dose and the certain detection of an effect may be a matter of years. This is one reason why the early warning systems being developed [87] are of such interest.

The operational disadvantage to the critical load approach is that logically there can be no reason not allow deposition (or pollutant concentration) to rise to the critical load/level set. Even if 'best available technology' could keep values well below the critical load/level, it could be argued that there would be no point in doing so as, by definition, no damage will occur up to that value. In practice, it is doubtful whether such an unwise attitude would gain acceptance for at least two reasons. Firstly, critical load values are only estimates and have uncertainties associated with the values. Secondly, sensitive areas tend to be relatively evenly spread, over Europe at least, and rather widely dispersed [13]. By meeting more stringent critical loads it will be likely that other less-sensitive areas would be kept well below the higher critical load value assigned to them.

5. TARGET LOADS

A critical load is considered an inherent property of an ecosystem. But it is possible to use critical load estimates as a basis to set a target load [12, 65, 73]. The target load value can form the basis of emission reduction strategies to reach area deposition goals. A target load value may be set above the critical load (if a certain degree of damage is regarded as acceptable, in order to set a realistically achievable deposition goal or to meet some socio-political requirement). Target loads might be set below a critical load value if it is thought this would allow more rapid ecosystem recovery to occur.

Target loads are useful in another way: at present it is only possible to estimate deposition rates over a wide area from meteorological atmospheric transfer models such as those developed by the Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe (EMEP). The estimates of atmospheric transfer from emitting sources to receptor areas (for sulphur and nitrogen) is based on a grid of 150 x 150 km squares (the 'EMEP grid square'). The relation between emission abatement and reductions in deposition to meet a critical or target load is thus initially most easily managed in abatement strategy terms of allotting an aggregated critical load value for a grid square. It may be a value based upon the mode for that grid square, a mean value (or weighted mean) or simply be the most stringent value represented in the grid square. Thus, a value not inherently representative of the total area may be identified that is more correctly described as a target load [60] than a critical load.

6. CRITICAL LOAD ESTIMATIONS

Four main approaches to the derivation of critical load values have been adopted:

- estimations based on empirical relationships;
- estimations based on proton deposition/production and consumption considerations (budget studies);
- estimations based on 'process models' of eco-systems;
- estimations based on palaeolimnological investigations.

6.1. Empirical methods

In some of the earliest work that led to critical load estimations, Elder and Brydges (1983) and Brydges and Neary [9] derived an interim 'target loading' which considered that the lakes had assumed a steady state with respect to acidification. They used observations of the distribution of damage to fish stocks along a gradient of sulphur deposition in Canada in lakes with similar catchment characteristics. They recorded the deposition at which damage to fish stocks became evident. Effects were seen as deposition reached 25 kg SO_4 ha^{-1} yr^{-1} but were not measurable in areas where the wet sulphate deposition was less than 10-15 kg SO_4 ha^{-1} yr^{-1}. The interim 'target loading' at which all but the most sensitive lakes were protected was set at 20 kg SO_4 ha^{-1} yr^{-1}. In areas where surface water alkalinity exceeded 200 ueq l^{-1} higher loading rates were considered acceptable.

Henriksen [35] developed an empirical model based on the hypothesis that the acidification of freshwater can be envisaged as a titration of a bicarbonate solution with strong mineral acids and showed how it was possible to estimate the pre-acidification alkalinity. pH in the lake is considered to be a function of the original alkalinity of the lake water and the acidity of the rain falling on the watershed and it was therefore possible to predict the pH of a lake of known Ca + Mg concentration. Henriksen, Dickson and Brakke [36] defined the critical load as depositions which will maintain a lake water at pH 5.3 since above this value lakes are still within the bicarbonate buffering system, there are no strong acids present and aluminium concentrations are below toxic levels. Using the empirical model, which has become known as the Steady State Water Chemistry Method for critical load evaluation [75], it is possible to predict what deposition value will keep the lake water above pH 5.3. It is suggested that this is 20-40 keq km^{-2} yr^{-1} for the most sensitive Norwegian lakes.

Acidification will lead to an increase in the Ca levels in lakes which will result in an overestimate of the original alkalinity. It will therefore take a higher deposition to depress lake pH by the same amount as if there had been no increase in Ca concentrations. The so-called F-factor (base cation change factor) was initially set at 0.2 [36]. The F-factor is defined as:

$$F = \frac{(Ca^{*} + Mg^{*})}{SO_4}$$

where * indicates 'non-marine'. F will vary between 0 and 1 [37]. The F-factor is assumed to vary as a function of the base cation concentration and increases with the base cation concentration [37]. It is used to adjust the critical load estimate.

It follows that lakes of different original alkalinities will follow different titration curves of acidification and Dickson [21] used observed data from Swedish lakes which had different non-marine Ca + Mg concentrations and received different amounts of sulphate deposition to predict the pH of lakes under a given deposition (Figure 1). Dickson [21] set the threshold at pH 6.0 assuming that there is damage to aquatic ecosystems below this pH. For the most sensitive lakes this resulted in a critical load of between 10 and 20 keq km^{-2} yr^{-1}.

Another empirical approach to setting critical loads is to set a target sulphate concentration in runoff or leaching rate to lakes [36]. Dickson [21] found that sensitive lakes will be acidified if sulphur leaching exceeds 0.3-0.5 g S m^{-2} yr^{-1}. The critical load would be the deposition causing this leaching rate.

Minns, Elder and Moore [60] carried out critical load determinations based on the response of fish to changing lake pH. They used an empirical model developed by Jones, Browning and Hutchinson [45] to describe the response of lake pH to acidic deposition. This model calculates the steady state alkalinity of a lake from the original alkalinity and the change in alkalinity due to acidic depositions. The alkalinity is then related to pH using an empirical relationship derived from a surface water database for Eastern Canada. Regionalization of the model was carried out by dividing the study area into 'sub-regions' based on site characteristics such as land use and hydrology. Using data from within the sub-regions it was possible to generate pH profiles which could then be related to the biological impacts through pH relationships in a biotic response model developed from observational data. The biological impacts model was based on pH minima curves for freshwater fishes (the minimum pH at which the fish species had been observed in lakes) in particular regions. Using a weighted random sampling technique for regional species-pH minima data, Minns, Elder and Moore [60] were able to relate pH decrease to species loss, in terms of the original pH level of the lake and the rate of deposition through an empirical lake chemistry model. Critical load estimates of 20 keq km^{-2} yr^{-1} were derived for lakes in eastern Canada that would give a high chance of protecting most lakes.

Meijer [57] set critical loads based on Dutch experience of nitrogen deposition on various ecosystems. The critical loads were based on the NH_4:K, NH_4:Mg or Al:Ca ratios in the soils of forest ecosystems. Observations of forest health in response to changes in these parameters were made. These ratios should not exceed 5, 5 and 1 respectively which corresponds to a nitrogen deposition of about 20 kg N ha^{-1} yr^{-1} for most forest ecosystems in The Netherlands. However, in order to minimize nitrate leaching to the drinking water standard (50 mg l^{-1}) the deposition was adjusted to 10 kg N ha^{-1} yr^{-1}. The critical value for NH_4:Mg ratio is revised to 10 [38] which gives rise to a critical load of about 15 kg N ha^{-1} yr^{-1} for sensitive sites. Van Dijk and Roelofs [22] reviewed experiments to determine the deposition at which nitrogen caused vegetation changes. In small softwater ecosystems the critical load to prevent vegetational change was 20 kg N ha^{-1} yr^{-1}.

Liljelund and Torstenson [54] reviewed the N deposition rates in various studies which were implicated in changes in plant community composition. Sites with deposition rates of 20 kg N ha^{-1} yr^{-1} were found to have had changes in floristic composition and the critical load therefore would have to be set at a lower value (15 kg N ha^{-1} yr^{-1}) for most ecosystems but at 10 kg N ha^{-1} yr^{-1} for very sensitive ecosystems.

Gundersen et al. [33] have suggested that the deposition of nitrogen should not exceed the uptake by plants (5-15 kg N ha^{-1} yr^{-1} in Nordic coniferous forest ecosystems) in order to prevent acidification of the soil. Rosén [70] calculated critical loads on the basis of the capacity of woody biomass to accumulate nitrogen and also the increased depletion of base cations from the soil in response to increased growth rates. The critical load set in this way varies with site quality and for Scandinavian forests will probably vary between 5-15 kg N ha^{-1} yr^{-1}.

Nilsson and Grennfelt [65] give critical loads for nitrogen (CL_N) using:

$$CL_N = N_{upt} + IM_{acc} + L_{acc}$$

where N_{upt} is the uptake in biomass, IM_{acc} is the acceptable accumulation in the soil and L_{acc} is the acceptable leaching from the system. Using this method they derive critical load ranges for nitrogen, dependent on the productivity of the site, which vary from 3 to 20 kg N ha^{-1} yr^{-1}.

6.2. Ion budget studies

Nilsson [64] calculated critical loads based on a 'proton budget' approach. The critical load is calculated by ensuring that the total input rate of hydrogen ions ($H^{\pm}_{in}$) is less than or equal to the weathering rate (WR) of base cations:

$$WR \leq H^{+}_{in}$$

The input of hydrogen ions consists of the following components: wet deposition ($H^{\pm}_{wet}$), dry deposition ($H^{\pm}_{dry}$), internal processes ($H^{\pm}_{int}$), excepting the biological transformations of nitrogen, and the net effect of the deposition of nitrogen (assuming $NH_4^{\pm}$ leaching is negligible):

$$H^{+}_{in} = H^{+}_{wet} + H^{+}_{dry} + H^{+}_{int} + NH_4^{+}{}_{in} + (NO_3^{-}{}_{out} - NO_3^{-}{}_{in})$$

The weathering rate may be calculated from:

$$WR = BC_{out} + BC_{upt} - BC_{dep}$$

where BC_{out} is the output of base cations in drainage water, BC_{upt} is net uptake in perennial biomass and BC_{dep} is the base cation deposition. These factors must be measured or estimated in order to derive an estimate of the critical load by making certain assumptions.

Nilsson [64] simplified the calculation and derived the critical load or 'permissible deposition' ($H^{\pm}_{perm}$) from:

$$H^{+}_{perm} = WR - H^{+}_{in}$$

Critical loads were calculated for catchments in Scandinavia and North America which varied from 0 to 75 keq km^{-2} yr^{-1}, with critical loads for most of sensitive catchments of between 10-20 keq km^{-2} yr^{-1}.

Sverdrup and Warfvinge [74] also used budget study data to derive critical loads for specific catchments using:

$$CL = WR - BC_{upt} - nitrogen\ acidity - BC_{out}$$

where WR is weathering rate and BC base cation uptake and outflux. The critical load estimates using this method vary between 0 and 120 keq km^{-2} yr^{-1} for terrestrial ecosystems with most Scandinavian systems having critical loads around 30 keq km^{-2} yr^{-1}.

Weathering rates may be calculated by budget studies or measuring the depletion of cations from the upper part of the soil profile. Tamm [76] calculated the annual depletion rate of a podsol to be 7.5 keq km^{-2} yr^{-1} over 9000 years.

Eriksson [27] calculated the critical load for groundwater from budget studies by assuming that the critical load is equal to the alkalinity production down to any given depth of the soil. The critical load was set by reference to the suitability of the water for human consumption from dug wells. Critical loads for groundwater vary between 3-24 keq km^{-2} yr^{-1} at a depth of 3m and between 10 and 80 keq km^{-2} yr^{-1} at a depth of 10 m, dependent on the type of soil.

6.3. Process models

Various process models have been used to estimate critical loads. These include empirical models using process-oriented mechanisms in their structure, such as the MAGIC model [14], the RAINS Lake Model (RLM) of Kämäri and Posch [47] and the Model to Assess a Critical Acid Load (MACAL) of de Vries [83]. More complex models such as the Steady State Soil Chemistry Model (PROFILE) developed by Sverdrup and Warfvinge (1989) and RESAM, the Regional Soil Acidification Model [84] have been developed.

MAGIC [14, 15, 16] simulates the fluxes to and from the pool of exchangeable cations in the soil which will be affected by acidic deposition and give rise to changes in surface water chemistry. MAGIC is a whole catchment lumped parameter model attempting to describe catchment response without incorporating the detail of less easily measured mechanisms; it concentrates only on a small number of important soil processes. The model consists of two main sections:

- a soil-soil solution chemical equilibrium section taking into account sulphate adsorption, cation exchange, aluminium chemistry and dissolution of inorganic carbon;

- a mass-balance or budget section explaining the flux of major ions in terms of deposition, the weathering rate, base cation uptake and loss to runoff.

The equilibrium equations assume an instantaneous equilibrium but since the mass-balance section includes rates of weathering, uptake and deposition, this is a dynamic model which may be used to investigate the time aspects of surface water response to deposition. The output of the model is the streamwater chemistry including pH, alkalinity and aluminium concentrations. MAGIC can be used to derive critical loads by setting a critical value for either pH or alkalinity and running the model with different deposition loads.

The RAINS Lake Model RLM [47] assumes that only a few reactions between the soil and soil solution need to be considered to describe surface water chemistry. These include relationships between soil base saturation and soil solution pH and between the solid and liquid phases of aluminium. The change in base cations and therefore base saturation is determined by the movements of acids and bases into and out of the soil. This change is defined as:

$$\frac{dBC}{dt} = WR + BC_{dep} - SO_{4\,dep}$$

where $SO_{4\,dep}$ is the total sulphate deposition.

The model considers two soil layers and assumes that all runoff goes through the A layer and the routing of waters through the two soil layers is calculated from the maximum possible flow rate through the lower B layer. The output of the model is lake pH and alkalinity and again critical loads have been estimated by setting up a critical pH or alkalinity. Wright, Kämäri and Forsius [84] used a critical value of Ph 5.5 to calculate the critical loads for Finnish catchments.

MACAL is a model which can be used to assess the critical load of forest soils [88]. Here, critical values for aluminium concentrations and Ca:Al ratios are set at 0.2 $mmol_c\,l^{-1}$ and 1.0 respectively and the model calculates the yearly averaged calcium and aluminium concentrations in soil compartments of 10 cm up to 80 cm depth. The model predicts the element flux and water flux in given soil compartments at given levels of acidic deposition:

$$EL_{flux}(X) = EL_d + EL_e + EL_m + EL_w(X) - EL_u(X)$$

where $EL_{flux}(X)$ is the element flux at depth X, El_d is the deposition of the element, El_e is the foliar exudation of the element, El_m is the element mineralization, $El_w(X)$ is the accumulated element weathering to depth X and $El_u(X)$ is the accumulated element uptake to depth X.

MACAL simplifies soil processes by numerous assumptions. The model is run using different deposition scenarios and the Al concentrations and Ca:Al ratios at different soil depths are compared to the critical values mentioned.

The model developed by Sverdrup and Warfvinge [74] attempts to find the steady state equilibrium soil chemistry at any particular deposition rate and therefore ignores the time development of acidification or recovery. The soil is divided into any number of horizons and the Acid Neutralizing Capacity (ANC) production by various processes is calculated for each soil horizon. The processes considered are cation exchange, the weathering rate and biochemical processes including the transformation of nitrogen. In each soil horizon there is a mass-balance equation for ANC which calculates the change in ANC for that horizon from the ANC of the solution entering it, the ANC of the solution leaving it and the production of ANC within the soil horizon. The weathering rate is calculated in a separate sub-model which uses experimentally defined chemical reactions for most of the common soil minerals. The model is run until there is no change in ANC in any horizon and the new steady state is achieved. The model requires many input parameters for each soil horizon including the mineralogy, density and exposed surface area of the soil, the carbon dioxide partial pressure and base cation uptake rate by vegetation. The output is the soil solution composition including estimates of pH, calcium and aluminium concentrations and base saturation. Critical loads are estimated by running the model until the deposition produces a soil solution chemistry conforming to one of the three target values mentioned previously (page 4).

6.4. Palaeolimnological reconstructions

Flower and Battarbee (1983), Battarbee et al. (1985) and Renberg and Helberg [69] reconstructed the historical pH changes from the changes in the composition of diatom assemblages preserved in the sediments of lakes in Scotland and Scandinavia. From these pH reconstructions it has proved possible to suggest a critical load by either finding or estimating the deposition at which the rate of decrease in lake pH becomes significant or when it reaches a given value. Battarbee [3] plotted sulphur deposition against calcium concentration (as an indication of the lake sensitivity) of different British lakes and on this graph indicated which lakes had been acidified according to diatom analyses. There would seem to be an approximate sulphur deposition to calcium concentration ratio which separates the acidified lakes from the non-acidified which can then be used to indicate the critical load for any given lake.

7. CRITICAL LOAD ESTIMATES AND UNCERTAINTY

Critical load estimates are subject to uncertainties that arise from their method of calculation and from the accuracy of the input data. For example, empirical determinations have the virtue of simplicity and of emphasizing dose-response relationships but ignoring time related aspects; dynamic models take account of time in the response in making some of the calculations. In both methods different criteria may be adopted: the critical value for lake water in relation to adverse threshold effects on biota varies between pH 5.3 and 6.0. The outcome of such uncertainties can be seen in comparisons of critical loads arrived at for catchments using different methods of estimation (Table I).

8. MAPPING CRITICAL LOADS

Once critical load estimates are available it may be of interest to produce critical load maps. It is possible that such maps will be particularly useful in comparison with rates of acid deposition, in order to see the balance between the two and also where most effort is required to limit and control depositions so that ecosystems (and eventually buildings and structures, and human health) can be protected. In fact, as already indicated, such activities may form the basis of linking fuel use and other acid emitting processes, S and N emissions, atmospheric transport and deposition to cost-effective abatement procedures, in a cost-optimized way, to produce co-ordinated abatement strategies.

Critical load maps of acid deposition may be generated by calculation methods or by surrogate methods that attempt to assess the sensitivity of ecosystems to acidic depositions from readily available environmental information.

8.1. Calculation methods

Three different approaches to the calculation of critical loads, for the purpose of mapping, have recently been recommended [75]. They are essentially the methods already described and comprise:

- the Steady State Water Chemistry Method;
- the Steady State Mass-Balance Method;
- the Dynamic Modelling Method.

The three methods differ significantly in the data requirements.

8.1.1. The steady state water chemistry method

This applies to lakes and water courses. The pre-acidification base cation concentration is calculated using the present base cation concentration, site-adjusted employing an empirical F-factor, and an estimate of the background sulphate concentration is combined with this to obtain the original lake alkalinity. The deposition of strong acid anions that cause the original alkalinity to fall to a chosen alkalinity value is the site critical load.

8.1.2. The steady state mass - balance method

This method may be used for soils, and for groundwater and surface runoff water from catchments. It identifies the mean, long-term sources of acidity and alkalinity in the system and then determines the maximum acid input that will bring about a balance that is biologically 'safe'. Weathering rates, biomass acidity input, acid inputs from nitrogen transformations and alkalinity outflux are estimated. Models like MACAL referred to above can be used or more simple mass balance calculation performed.

Table I. Comparison of Critical Load Estimates for a Range of Catchments

Catchment	Aquatic (Aq)/ terrestrial (Te)	Critical load estimate (keq km^{-2} yr^{-1})	Method	Reference
Gårdsjön (S.W. Sweden)	Aq	0 - 5	Ion budget	Sverdrup and Warfvinge (1988)
	Aq	20	Process model	Wright, Kämäri and Forsius (1988)
	Aq	8 - 38	Process model	Sverdrup, de Vries and Henriksen (1989)
	Aq	8	Empirical model	Sverdrup, de Vries and Henriksen (1989)
	Te	0 - 50	Ion budget	Sverdrup and Warfvinge (1988)
	Te	10 - 33	Ion budget	Nilsson (1986)
	Te	20	Process model	Sverdrup, de Vries and Henriksen (1989)
	Te	15 -40	Process model	Sverdrup and Warfvinge (1988)
Sogndal (Norway)	Aq	0	Ion budget	Sverdrup and Warfvinge (1988)
	Aq	21	Process model	Wright, Kämäri and Forsius (1988)
	Te	5 - 55	Ion budget	Sverdrup and Warfvinge (1988)
Birkens (S. Norway)	Aq	25	Process model	Wright, Kämäri and Forsius (1988)
	Aq	4	Process model	Sverdrup, de Vries and Henriksen (1989)
	Te	25 - 44	Ion budget	Nilsson (1986b)
Woods Lake (USA)	Aq	20	Process model	Kämäri (1986)
	Aq	0 - 70	Ion budget	Sverdrup and Warfvinge (1988)
	Te	15 - 46	Ion budget	Nilsson (1986b)
	Te	0 - 45	Ion budget	Sverdrup and Warfvinge (1988)
	Te	25 - 35	Process model	Sverdrup and Warfvinge (1988)
Kloten (C. Sweden)	Aq	0	Ion budget	Sverdrup and Warfvinge (1988)
	Te	2 - 28	Ion budget	Nilsson (1986b)
	Te	0 - 20	Ion budget	Sverdrup and Warfvinge (1988)
Kullarna (C. Sweden)	Aq	0 - 55	Ion budget	Sverdrup and Warfvinge (1988)
	Te	15 - 85	Ion budget	Sverdrup and Warfvinge (1988)
	Te	4 - 6	Ion budget	Nilsson (1986b)

8.1.3. Dynamic modelling

Methods using dynamic modelling incorporate time (rate factors) into the estimation of critical loads. They are applicable to soils, ground and surface waters, and to episodic events. There are quite a large number of models. Data on up to 30 parameters may be needed to run the model. This data will need to be obtained from field measurements or from site characteristics using site functions. These models attempt to make use of an understanding of processes in the system and should, when employed in a satisfactory manner, give the most realistic and reliable critical load estimates.

8.2. Other methods

Progress has been made in mapping calculated critical loads: in Norway [37] and in Sweden [74]. However, abatement strategy models being developed as a tool for investigating optimum strategies for emission abatement require information for a whole region so that target loads can be identified.

As an interim measure, an assessment of the relative sensitivity of ecosystems to acidic depositions might prove useful so that tentative critical load values could be applied to the relative sensitivity classes and form the basis of target loads that could be used in abatement strategy models. One such attempt at mapping the relative sensitivity of ecosystems to the indirect effects of acidic depositions is now described.

9. MAPPING THE RELATIVE SENSITIVITY OF ECOSYSTEMS

An assessment of the relative sensitivity of ecosystems to acidic depositions can be obtained from environmental site factors which are most likely to influence the response of the ecosystems to those depositions. Use of a limited number of factors, which are readily accessible, give a relatively simple and widely applicable assessment amenable to mapping in reasonable detail over large areas. For example, Europe can be mapped using bedrock lithology, soil type, land use and mean annual rainfall statistics. When these factors are combined using weights, the resulting sensitivity refers to the likely effect of acidic depositions on ecosystem function and structure.

9.1. Environmental factors

Within each factor a limited number of categories are distinguished according to the way in which they might affect sensitivity. Rock type is assigned to one of two categories depending on the weathering rate, reflecting the importance of mineral weathering in the buffering of acidic inputs to the system. Soil type is assigned to one of two categories dependent on the physical and chemical properties which determine the likelihood of the soil chemistry entering the aluminium buffer range where most of the acid buffering is carried out by aluminium compounds in the soil and where aluminium concentrations in the soil begin to rise. Land use is assigned to one of four categories based on the effect that the vegetation has on soil formation, the interaction between the canopy and deposition and on the effect that the vegetation has on site hydrology. The amount of rainfall determines the site hydrology and also the amount of ions leaching from the soil and is assigned to one of two categories.

9.1.1. Rock type

The relative rates of weathering of different rock types has been reviewed and consideration given to the mineralogical and chemical composition of the different rock types. The resulting classification is shown in Table II. The slow weathering rate rock types in Group A (Table II) are designated Category I. Unfortunately, the map of Europe-wide geology shows sedimentary rocks by age and not type. This has been overcome by assigning to Group A rocks of Pre-Cambrian and Lower Palaeozoic age, which are generally slow-weathering and low in carbonates [49]. Other, faster weathering rock types (Groups B, C and D) are assigned to Category II. Sites with Category I rock types have higher sensitivity than those with rock types of Category II.

Table II. The Acid Neutralizing Ability of Rock Types

Group	Acid neutralizing ability	Rock type
A	None - low	Granite, syenite, granite-gneisses, quartz sandstones (and their metamorphic equivalents) and other siliceous (acidic) rocks, grits, orthoquartz, decalcified sandstones, some quaternary sands/drifts
B	Low - medium	Sandstones, shales, conglomerates, high grade metamorphic felsic to intermediate igneous, calcsilicate gneisses with no free carbonates, metasediments free of carbonates, coal measures
C	Medium - high	Sligtly calcareous rocks, low-grade intermediate to volcanic ultramafic, glassy volcanic, basic and ultrabasic rocks, calcareous sandstones, most drift and beach deposits, mudstones, marlstones
D	'Infinite'	Highly fossiliferous sediment (or metamorphic equivalent), limestones, dolostones

Source: [49, 55, 67].

9.1.2. Soil type

The physical and chemical soil attributes which are assumed to give an indication of whether soils are in danger of entering the aluminium buffer range are shown in Table III. The data for typical soil profiles for all the soil types in the FAO classification are given in the book accompanying the FAO Soil Map of the World [29] and the Soil Map of the European Communities [23]. On the basis of this information the soil types with low pH, base saturation (V), Ca content and high proportion of sand were assigned to Category I, and other soil types to Category II. Table III shows summary data for the two soil categories. Sites with Category I soil types are more sensitive than those with Category II soil types.

Table III. A Summary of the Soil Data for the Two Soil Categories

Soil category		pH	CEC (meq 100g^{-1})	V (%)	Sand (%)	Ca content (meq 100g^{-1})
I	Mean	4.2	23	8	61	1.52
	s.d.	0.27	9.5	2.5	21	1.7
	Range	3.8 - 4.5	14 - 33	6.13	30 - 94	0.1 - 4
II	Mean	6.7	33	57	30	18
	s.d.	1.01	39	31	26	20
	Range	4.9 - 8.4	2 - 182	7 - 100	5 - 97	0.2 - 100

Source: [23, 29].

9.1.3. Land use

Four categories of land use are taken to be the minimum number which have to be considered in the assessment of sensitivity to acidic deposition (coniferous forest; deciduous forest; intensively managed agricultural land; other, relatively unmanaged land such as heath or rough grazing).

Coniferous forest is considered to increase site sensitivity to the greatest extent. This is due to the way in which conifers confer certain hydrological characteristics to sites [59], and because of the characteristics of the typical acid more organic layer formed under coniferous forest stands [58]. The organic layers are an important part of the plant rooting zone and substantial amounts of water reaching lakes may travel through the organic layer, particularly in high rainfall areas [18, 49]. Trees act as funnels for acidic rain water and acidic stem flow may cause a decrease in pH at the base of trees. The filter effect by which pollutants are efficiently scavenged from the air, increases the deposition of pollutants [40, 81]. Coniferous trees are particularly efficient at filtering acidic pollutants from the air and as coniferous forest cover increases within catchments, so does the deposition of sulphur compounds [39].

Rough grazing and heathland vegetation produce more humus and so this type of vegetation is also considered to increase site sensitivity, though to a lesser extent than coniferous forest as the filter effect is not so large [39] and hydrological modification not so great [62].

Deciduous forest vegetation produces less acid, mull humus which has a higher decomposition rate and lower organic acid production rate than a more humus [58]. Hardwoods often have deep roots which bring up nutrients from lower soil horizons leading to a certain amount of surface soil layer enrichment [7]. Sites with deciduous forest vegetation, therefore, have a lower relative sensitivity than sites with vegetation causing the production of more humus.

It is assumed that practices such as fertilizer and lime application will artificially maintain high pH and base saturation levels on intensively managed land and reduce sensitivity accordingly [2].

9.1.4. Amount of rainfall

As the amount of rainfall increases, the base cation, aluminium and other acid ion leaching rates increase due to the increased flow of water in the soil. Build-up of the organic layer occurs in high rainfall sites, reducing the ability to buffer acidic inputs [49]. Regions with an annual average rainfall greater than 1,200 mm are categorized as having a higher sensitivity than those receiving less.

9.2. Combining factors

The sensitivity of an ecosystem is the result of the combined influence of the site factors determining ecosystem response to acidic depositions. Therefore, in order to derive a relative sensitivity ranking, the factors described have been combined by addition, since this is the clearest and simplest form of combination. The relative importance of the different factors in determining sensitivity is reflected by the weights shown in Table IV which are used in the combination.

Land use is weighted most heavily (Table IV) due to the large difference between the effect that coniferous forest and arable land has on the soil. The high weighing given to the rock type reflects the relevance of mineral weathering to the neutralization of acids. Soil is weighted less heavily since part of the effect of soil in neutralizing acids, namely the weathering of minerals, is assumed to be reflected by the bedrock lithology. The effect of rainfall is not considered to affect the sensitivity to the same degree as either mineral weathering or land use.

The combination using the weights produces eight classes of relative sensitivity to acidic depositions (0-7). In view of the restricted amount of critical load information in Europe and also in consideration of the use of the map as a basis for applying these critical loads, the seven sensitivity classes have been reduced to five by merging some of the sensitivity classes. The higher sensitivity rankings were combined in pairs (2+3; 4+5; 6+7) and with Classes 0 and 1 gives sensitivity classes 1 to 5 which are shown on the map (Figure 2).

The map is designed to show that for a unit of acidic deposition aquatic and terrestrial ecosystems in the more sensitive areas will be more affected than those in less sensitive areas. It is assumed here that the sensitivity of aquatic and terrestrial ecosystems is controlled by the same factors and that the relative sensitivity will be the same in the same catchment. However, this does not mean that the absolute sensitivity will be equal for the aquatic and terrestrial ecosystems and, in many cases, the critical loads suggested for the same catchment are different and often higher for terrestrial ecosystems.

The validity of the relative sensitivity map (Figure 2) will depend upon a number of assumptions:

- that the four factors chosen account for the major sources of the variation in sensitivity;
- that the division of the factors is correct;
- that the weights applied to the factors reflect the real importance of the different factors in controlling site sensitivity;
- that the method of combination is the optimal way to derive a measure of site sensitivity from the controlling factors;
- that the same methodology can be applied to the whole region.

Table IV. Division of Site Factors into Categories and Associated Weights for Use in Combination

Factor	Weight	Category	Weighting
Rock type	2	I siliceous, slow weathering rocks	1
		II faster weathering rocks	0
Soil type	1	I major acid buffering <pH 4.5	1
		II major acid buffering >pH 4.5	0
Land use	3	I coniferous forest	1
		II rough grazing	2/3
		III deciduous forest	1/3
		IV arable land	0
Rainfall	1	I >1,200 mm (annual average)	1
		II <1,200 mm (annual average)	0

9.3. Use of critical loads with the sensitivity map

The map produced shows relative sensitivity. Target load values are assigned to the classes of relative sensitivity. The target loads are based on critical load estimates derived using the methods outlined above. Here the targets have been set at the same level as the critical loads for the ecosystems.

The target values have been obtained by comparing the critical load values for specific sites to the sensitivity class of the region in which the site lies. Many of the terrestrial and aquatic ecosystems in Scandinavia, within regions having the highest sensitivity (class 5) according to Figure 2, have been allocated critical load values of 20 keq $km^{-2}\ yr^{-1}$ [63, 65]. This level of deposition has been designated the target for this sensitivity class. By similar comparisons targets in Table V have been applied to the five classes of relative sensitivity.

Table V. Target deposition levels applied to the relative sensitivity classes

Relative sensitivity class	Targets (keq $H^+\ km^{-2}\ yr^{-1}$)
1	>160
2	160
3	80
4	40
5	20

The values in Table V compare well with the range of critical loads suggested by Nilsson and Grennfelt [65] for soils with different bedrock types and with minerals of different weathering rates.

10. THE CONTRIBUTION OF NITROGEN COMPOUNDS TO ACIDIFICATION

The critical load for acidification refers to the total anthropogenic deposition of acidifying substances (from sulphur sources and proportion of nitrogen leached). Sulphur deposition usually accounts for much of the acidic input to ecosystems but nitrogen may also be a major contributor to the acidification of soils and waters. Sulphur and nitrogen deposition will only acidify the soil when deposited sulphate and nitrate anions are leached. Plant requirements for sulphur are low, and the sulphate adsorption capacity of most soils in Europe is also relatively low. This means that most of the deposited sulphur will be free to leach from the soil and cause acidification. Nitrogen, however, is a major plant nutrient and is often a factor limiting growth in European ecosystems. Not all nitrogen deposited therefore leaches from sites and so only a proportion of deposited nitrogen will acidify ecosystems. It is necessary to obtain estimates of the proportion of deposited nitrogen that will be subject to leaching if the 'nitrogen component' of total acidity is to be included in the estimates.

In order to predict the degree of regional nitrate leaching it is necessary to:

- determine the regional uptake/removal of nitrogen;
- determine the degree of immobilization.

The degree of acidity production (N_{acid}) due to nitrogen depositions (i.e. the amount of nitrogen leaching) may be estimated from:

$$N_{acid} = (N_{deposition} - N_{uptake}) \cdot (1 - N_{immobilized})$$

where $N_{immobilized}$ is the proportion of excess N immobilized in the soil and $(1\text{-}N_{immobilized})$ is the proportion of the excess of deposition over uptake that is leached.

10.1. Nitrogen uptake

Nitrogen uptake rates depend upon biomass productivity and the optimal internal nitrogen concentration of plant species. The biomass productivity depends on climatic factors, the plant species making up the vegetation and site fertility [70, 77, 80]. The optimal range of internal nitrogen concentration is an inherent feature of species.

Table VI summarizes nitrogen uptake/removal rates for four main categories of land use. The estimates are approximate due to variation from site to site within a land use category. Regional uptake rates are illustrated in Figure 3.

10.2. Immobilization of nitrogen

Leaching of soil nitrogen not subject to uptake by plants and other organisms is controlled by factors affecting the rate of release of nitrate from organic matter (mineralization and nitrification), denitrification and solute leaching. Mineralization would seem to be affected to a large degree by the A horizon C:N ratio [33, 52]. Soils with A horizon C:N ratios of >25 tend to exhibit negligible mineralization and nitrate leaching rates, with C:N ratios of 15-25 intermediate leaching rates and C:N ratios <15, high leaching rates. The pH, often quoted as an important variable affecting nitrification rates, correlates well with C:N ratio, at least on a broad scale (Figure 4).

Soil drainage, dependent on soil texture, is a factor which affects the rate and degree of solute (e.g., nitrate) leaching. Soil moisture affects nitrate leaching rates. Dry soils leach little nitrate compared to wetter soils. The precipitation to potential evapotranspiration ratio (P:E ratio) is used as an indicator of soil moisture conditions:

- P/E =< 0.5 : very dry soils;
- P/E = 0.5 - 1.0: moderately moist soils;
- P/E => 1.0 : moist soils.

Table VI. Approximate Nitrogen Uptake Removal Rates (N Uptake) for Different Land Use Types

Land use category	N removal rate (kg N ha^{-1} yr^{-1})
Heath/rough grazing	2.5
Forest - Northern Boreal	6
- Rest of Europe	15
Arable/rich pasture	40

Source: [33, 34, 70, 80].

Steep topography increases the rate of leaching. Altitude may be taken as a crude substitute for topography. Regions with an altitude >1,000 m are considered to have steep topography compared with regions of an altitude <1,000 m.

Table VII shows the categories of the main factors, together with estimates of the degree to which the different categories affect nitrate leaching. The combined effect of the factors on nitrate leaching is considered to be a multiplicative. For example, sites with a C:N ratio of >25 are considered to only leach 10 per cent of the available nitrate in the soil, the rest being immobilized. If this site also is poorly drained, then only 50 per cent of the 10 per cent already leaching will be leached (i.e., only 5 per cent of the available nitrate will leach). Single values have been allocated to the relevant ranges shown in Table VIII. These values are used in calculations of the percentage of excess N ($N_{deposition}$-N_{uptake}) leached. The distribution of these percentages are illustrated in Figure 4.

Once N deposition is known it is possible to obtain an estimate of the regional N leaching, that constitutes the N contribution to total acidity, from the maps for N_{uptake} (Figure 3) and the proportion (or percentage) of the excess nitrogen that leaches (1-$N_{immobilization}$) as shown in Figure 4. The amount of acidity produced by nitrogen depositions can then be summed with that due to sulphur depositions to give a value of total deposition of acidifying substances from anthropogenic sources. The total acid load should include ammonium depositions, estimates of which can now be derived [25, 71].

Table VII. The Degree to Which Site Factors Affect the Leaching of Available Nitrate.[1].

Factor	Category	Proportion of nitrate leached
C:N Ratio	< 15	1.0
	15 - 25	0.5
	> 25	0.1
Drainage	Well drained	1.0
	Poorly drained	0.5
P/E Ratio	> 1.0	1.0
	0.5 - 1.0	0.5
	< 0.5	0.1
Relief	Sharp	1.0
	Shallow	0.75

Note: [1] *Numbers refer to the proportion of available nitrate that will be leached.*

Table VIII. Values for the Proportion of Excess Nitrate Immobilized

Calculated values of N immobilized	Value used in calculations	Percentage excess nitrate leched
0.00 - 0.075	0.05	5
0.075 - 0.15	0.10	10
0.15 - 0.30	0.20	20
0.30 - 0.60	0.40	40
0.60 - 1.00	0.80	80

10.3. Estimates of the contribution of N-depositions to total acidity

Data from European sources [10, 68] suggest that observed leaching rates range from 0.1 to 20 kg N ha^{-1} yr^{-1}. Nitrogen deposition rates of 2 to 50 kg N ha^{-1} yr^{-1} have been measured. The leaching rates estimated by the method outlined above are in the range of 0-38 kg N ha^{-1} yr^{-1}.

Popovic [68] measured deposition rates in Central Sweden of approximately 10 kg N ha^{-1} yr^{-1} and observed leaching of about 0.1 - 0.4 kg N ha^{-1} yr^{-1}. The leaching rate calculated from the method suggested here for this area is 0.4 kg N ha^{-1} yr^{-1}. In the Haute Ardenne, Buldgen and Remack [10] measured leaching of 13 kg N ha^{-1} yr^{-1} under an approximate deposition of 35 kg N ha^{-1} yr^{-1}. The calculation made here is of leaching at 8 kg N ha^{-1} yr^{-1} so there is relatively good agreement although much more checking against measured rates is required.

11. CRITICAL LEVELS FOR DIRECT EFFECTS OF POLLUTANT GASES

11.1. The sensitivity of vegetation to SO_2

Various site factors alter the response of plants to SO_2, and the assessment of sensitivity to direct effects of sulphur dioxide concentrations is designed to show where damage to plants by SO_2 are most likely to occur.

SO_2 may have chronic effects on plants at low concentrations during long exposures or in high concentrations may cause acute damage after short exposure times. In certain respects these two types of damage are quite different and have to be treated in a separate manner. It is important to determine which is most relevant to effects on plants in order to predict where plants will be most sensitive.

11.1.1. Methodology

The approach used to estimate relative sensitivity to direct effects of pollutant gas concentration is to assess the environmental factors which influence the action of SO_2 on plants and from knowledge of their effect on plant response deduce the broad regional distribution of ecosystem relative sensitivity in Europe. The method used identifies a small number of the most important environmental site factors influencing plant sensitivity and divides these into a small number of categories. Weights are used to combine the controlling variables which broadly represent the degree to which the site factors influence plant sensitivity.

Site factors influencing the response of plants to SO_2. Site factors were selected on the basis of the importance of their effect on sensitivity to SO_2, the unambiguous way in which they influence sensitivity, the general availability of information on them in a Europe-wide context and susceptibility to mapping procedures, their overall integrative nature, and the relative permanence of applicability to an area.

The factors used to assess the sensitivity of plants to SO_2, which fulfil these criteria are:

- the sensitivity of different plant species;
- factors affecting stomatal movement (soil moisture);
- soil nutrient status;
- Winter conditions (mean January temperature).

The presence of other gaseous pollutants is an important factor influencing the response to SO_2 but is not directly included in this sensitivity assessment.

Species sensitivity to SO_2 - Plant species vary in their sensitivity to chronic and acute effects of SO_2 uptake [32, 53]. The relative sensitivity of plant species has been investigated using experimental determinations and observation of impacted sites. Much of the information is based on experiments using acute doses of SO_2 and the correlation between sensitivity to acute and chronic effects is poor [32].

It would appear in general that evergreen vegetation (especially coniferous trees) are more sensitive to SO_2 than deciduous trees [6, 32, 44, 53, 78]. 'Natural vegetation' has also been considered to be very sensitive to SO_2 and changes in the species abundance within the community may occur at low concentrations. Within each of these broad classes there is wide variation in the sensitivity of different species and this seems particularly true of agricultural species which exhibit a broad spectrum of sensitivity. It would seem, however, that many grain crops and important grass species have similar sensitivity to deciduous trees [32, 44, 53]. A simple separation of sensitivity of different land use types to SO_2 has been derived (Table IX).

Factors affecting stomatal opening (soil moisture) - The clearest relationship between pollutant uptake, subsequent injury, and an environmental factor is with relative humidity and soil moisture content. Leaf cells of plants with a limited water supply will have a low turgor pressure and stomata will tend to close, reducing the dose of SO_2 to the plant. Generally, more damage has been found to occur to plants under well-watered than under dry conditions [1, 48, 72] and at a high rather than a low relative humidity [66]. It is assumed that soil moisture status and relative humidity are the factors which most consistently affect the uptake rate of SO_2 and that, on a broad scale, relative humidity will tend to follow soil moisture content. The annual precipitation to potential evapotranspiration ratio (P:E ratio) is assumed to be an approximate indicator of soil moisture [85]. Three ranges of P:E ratio have been chosen to represent soil moisture contents in Europe: <0.5 (very dry); 0.5-1.0 (medium moisture); >1.0 (wetter soils).

Soil nutrient status - There are many experiments and field observations which indicate that SO_2 damage to plants increases under conditions of low soil nutrient status [17, 26, 50, 89]. The nutrient poor, acid soils, which are assumed to increase sensitivity of regions to indirect effects of acidic depositions (Section 9.1.2), are used to show areas which will tend to be more sensitive to SO_2 depositions due to low nutrient status.

Table IX. The Sensitivity of Land Use Types to SO_2

Sensitivity	Land use
Medium	Deciduous forest; arable or improved land
High	Coniferous forest/ evergreen vegetation and natural vegetation

Winter conditions - The severity of conditions in Winter affects the injury caused to plants by SO_2 due to interactions between the action of SO_2 and the climatic stresses on plants and effects of shorter day length and low irradiance [5, 19, 20, 30, 32, 41, 42, 56]. In order to account for the effects of winter conditions on sensitivity to SO_2 described, the mean January temperature is used. Areas where the mean January temperatures are less than -2.5°C are considered to be exposed to significant frost episodes and other Winter stresses, causing greater effects of SO_2 on plants.

Weighing procedures. Weights employed should be such that when the factors are combined the resultant distribution of sensitivity should relate to the observations and results from field sites. The species sensitivity and soil moisture status are considered the most important factors influencing sensitivity to SO_2 due to the large difference in the sensitivity of species and the importance of the uptake of SO_2 to subsequent injury. The weights applied to the factors are shown in Table X.

11.1.2. Mapping relative sensitivity to direct effects

The factors used to determine the relative sensitivity to direct effects have been digitized so that they can be combined. The land use types from the *Land Use Map of Europe* [28] and the *Types of Agriculture Map of Europe* [51]; annual rainfall and January temperatures from the *Climatic Atlas of Europe I* [86]; soil types from the *Soil Map of the World*, Volume V, Europe [29] and potential evapotranspiration rates from the *Agro-ecological Atlas of Cereal Growing in Europe: agro-climatic Atlas of Europe*, Volume 1 [79].

Six relative sensitivity classes result from the combination of the factors using the weights given in Table XI. The use of the map as a basis for assigning target concentrations, based on critical levels, is only feasible with a reduced number of classes due to the inability to achieve many different targets in view of the broad dispersion of SO_2 and errors associated with critical level estimates. Some of the sensitivity classes have very low cover in Europe and so are not justifiable as separate entities. The allocation of the six possible classes to three is shown in Table XI and the resulting map is shown in Figure 5.

Table X. Weights Used to Combine the Factors Influencing Sensitivity to Direct Effects of Sulphur Depositions

Factor	Weight	Category	Category weighting
Soil moisture (P:E ratio)	2	< 0.5	0
		0.5 - 1.0	0.5
		> 1.0	1
Species (Land use)	2	Deciduous forest and arable land	0.5
		Evergreen forest and natural vegetation	1
Soil nutrient status	1	High status	0
		Low status	1
Winter conditions (January temperature)	1	> -2.5°C	0
		< -2.5°C	1

Table XI. Combination of the Sensitivity Classes to the Three Classes to Which Targets are Applied

Original sensitivity class	Combined sensitivity class
1 - 2	1
3 - 4	2
5 - 6	3

11.2. Critical levels

As with critical loads, critical levels assume that there is a threshold concentration above which effects start to occur. The threshold concentration may change dramatically in the presence of other gaseous pollutants since interactions between gases may be synergistic. It is therefore necessary to set critical levels that take some account of the existence of other pollutant concentrations.

The experimental results on which assessments of critical levels are based tend only to specify the dose and plant species used in the experiment and do not describe the edaphic or climatic variables and in fact are generally fumigated under optimal conditions. It is therefore difficult to collect relevant data in order to set target concentrations to relative sensitivity classes which are partly based on such factors. Many fumigation experiments use high gas concentrations over relatively short time periods. This may lead to unrealistic results since Garsed and Rutter [31] found injury to *Pinus sylvestris* only after the second year of fumigation. Due to the form of the experiments carried out, the difficulty in reproducing experiments, and the lack of relevant information, setting critical levels can be difficult.

From experimental and observational data the critical levels for SO_2 in Table XII have been suggested [44]. These refer to SO_2 acting alone but assume that the other gaseous pollutants are kept below their respective critical levels (Table XIII).

11.3. Target concentrations

In order to set target concentrations on the basis of critical levels it is necessary to compare the conditions typical of the various relative sensitivity classes with the conditions of the experiments or field observations used to produce critical level estimates. It is also necessary to decide how to deal with the presence of other phytotoxic gases. It is considered that targets may be set as annual means. The potential importance of fluctuating levels is stressed by Jacobson and McManus [43] but Garsed and Rutter [31] conclude that for regions with an annual mean of about 100 µg m^{-3}, the main effect on plants under fluctuating regimes is attributable to the mean rather than the peak concentrations.

Table XII. Critical Levels for SO_2 Acting Alone

Species	Duration of dose	Critical level (µg m^{-3})
Sensitive plants	annual	20
Agriculture and horticultural	annual	30
All	24 hour (mean)	70

Table XIII. Critical Levels for NO_2 and O_3

	NO_2 $(\mu g\ m^{-3})$	O_3
1. Acting alone		
vegetation period	60	
winter 1/2 year	40	
24 h mean		50
8 h mean		60
4 h mean		80
2 h mean		110
1 h mean	800	150
0.5 h mean		300
2. In combination with SO_2 and O_3		
long term	20	

Source: [82].

The targets applied to the relative sensitivity classes are set in the expectation that other interacting gaseous pollutants will be present (NO_2 and O_3) and this will lower the target levels of SO_2 concentration. The target concentrations applied to the sensitivity classes are shown in Table XIV.

Table XIV. Target SO_2 Concentrations Applied to the Relative Sensitivity Classes

Relative sensitivity class	Target SO_2 concentration (annual average) $(\mu g\ m^{-3})$
1	50
2	25
3	12

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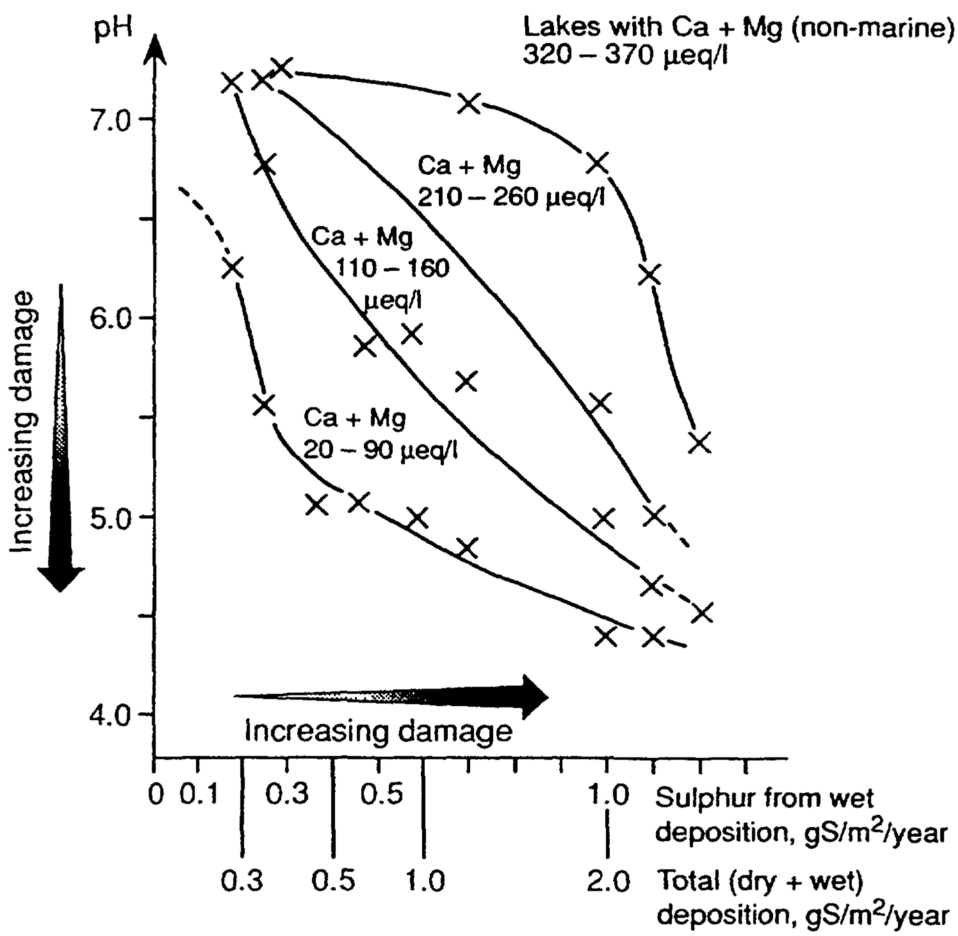

Fig. 1. The pH value in lakes (x) in Sweden of varying base production potential at different sulphur loadings. Total deposition was calculated from concentrations in runoff water (Dickson, 1986).

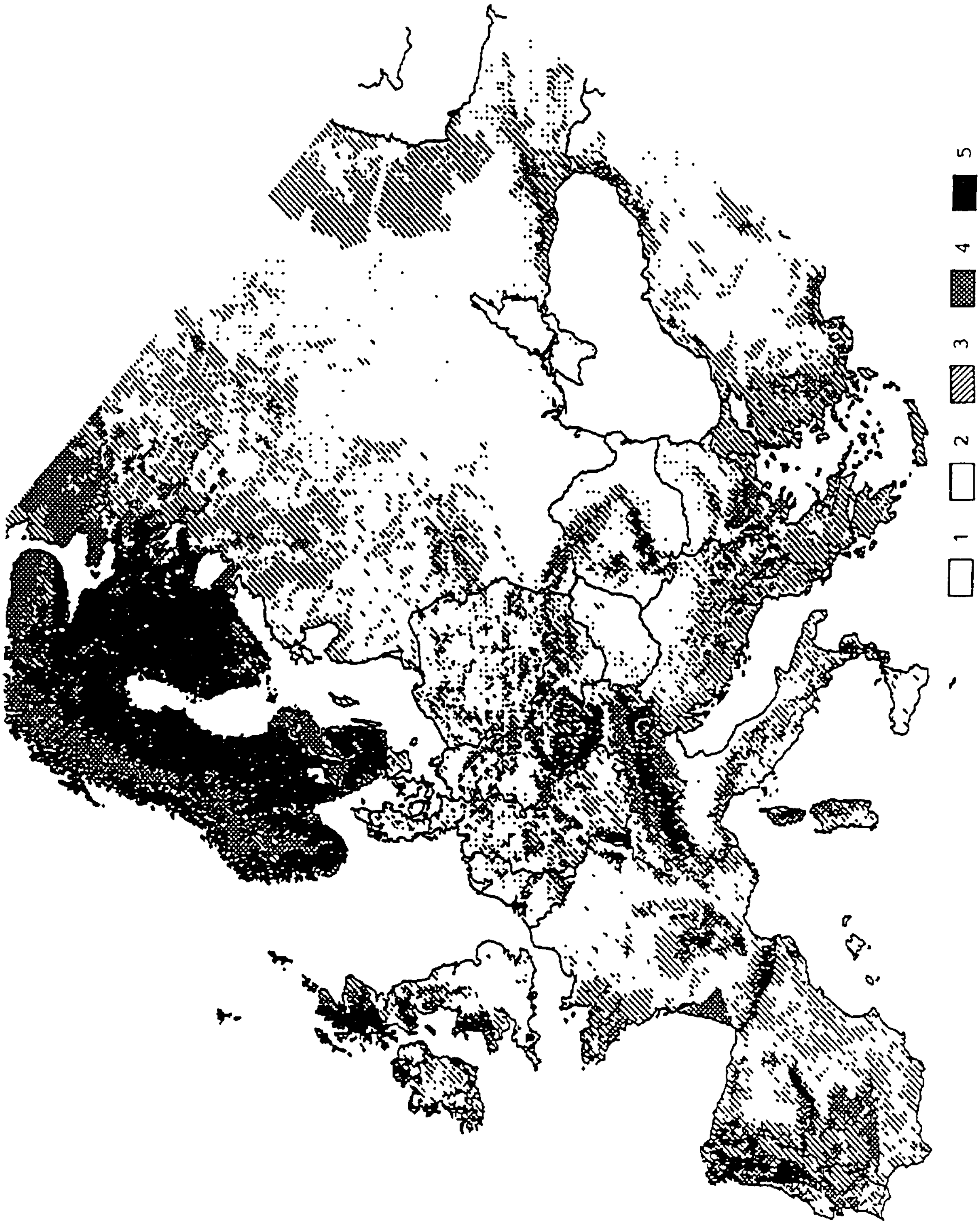

Fig 2. The relative sensitivity of ecosystems in Europe to acidic depositions (1, least sensitive; 5, most sensitive).

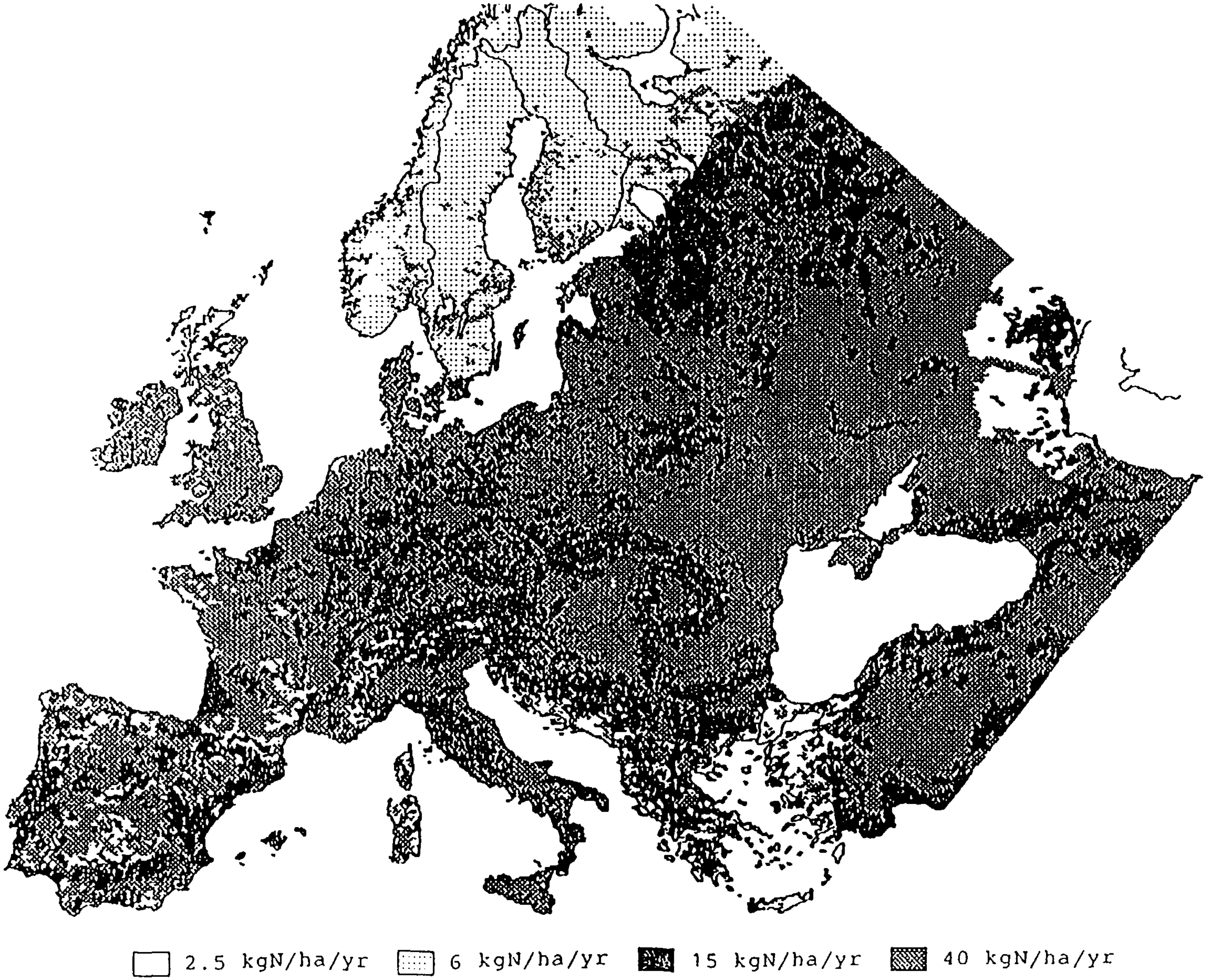

Fig 3. Regional nitrogen uptake rates (kg N ha^{-1} yr^{-1}).

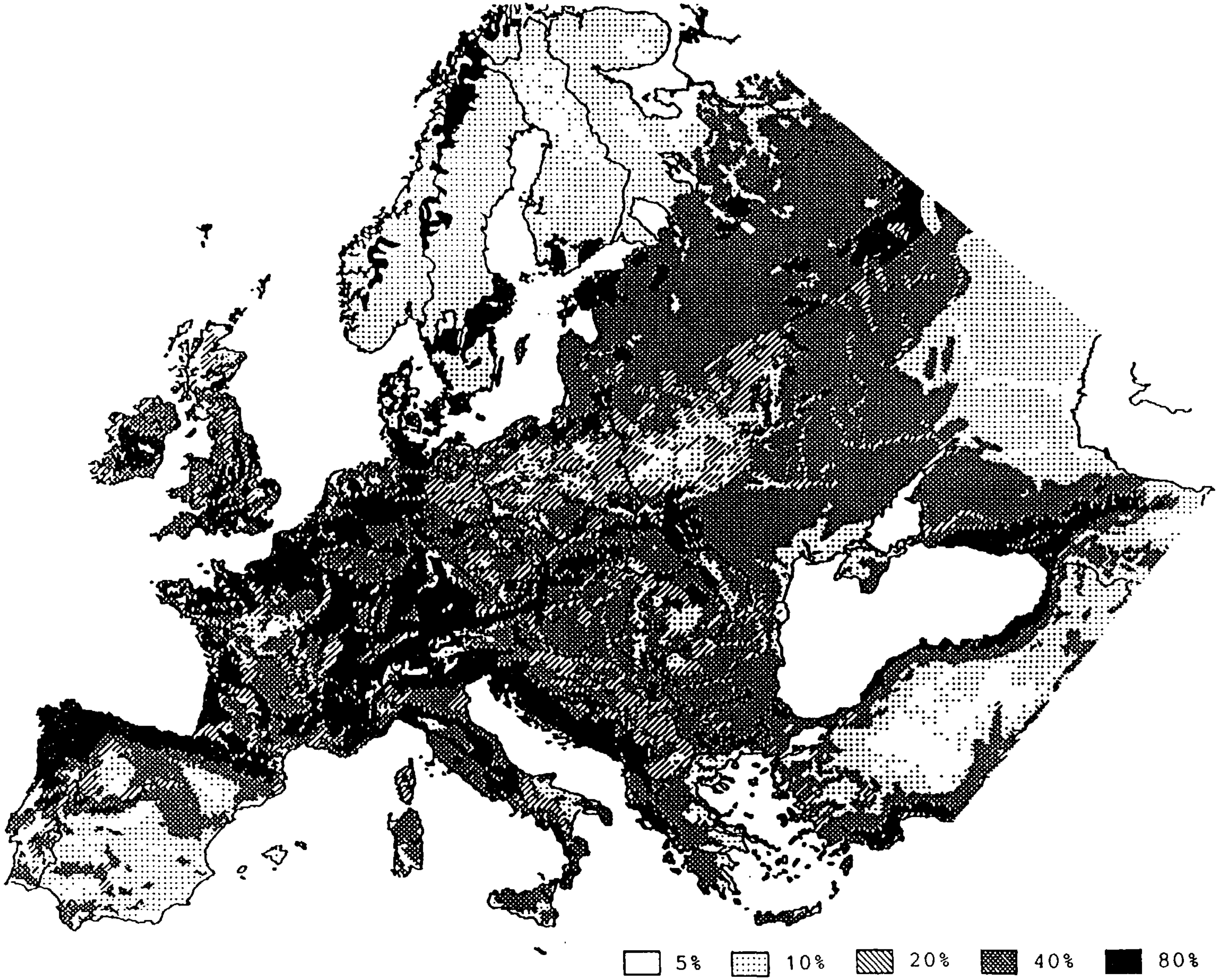

Fig 4. Percentage of excess nitrate leaching regionally from soil.

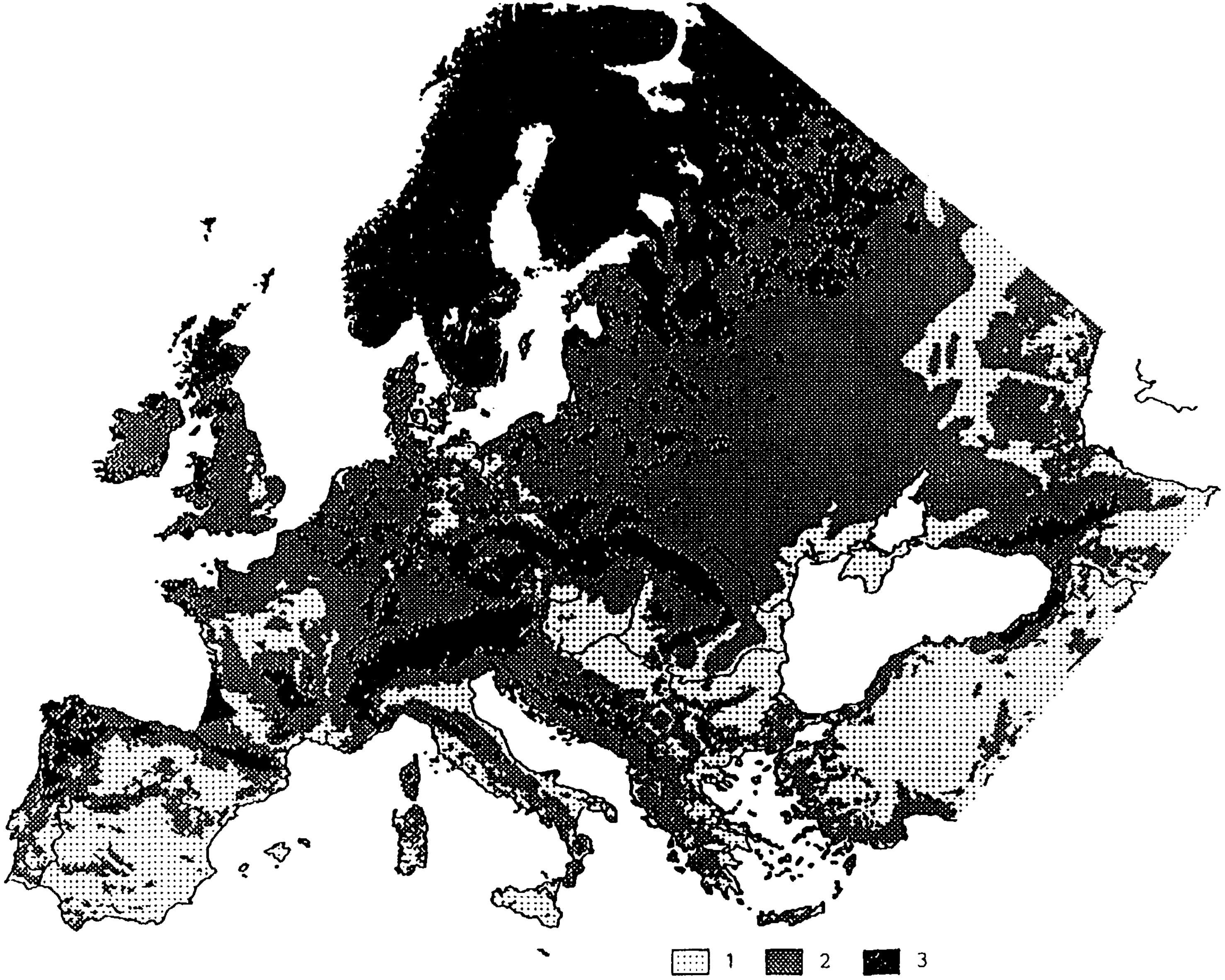

Fig 5. Relative sensitivity of ecosystems to SO_2 in Europe (1, least sensitive; 3, most sensitive).

COMMENTS ON ENERGY RISK ANALYSIS

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ABSTRACT: This aim of energy risk analysis is to determine the magnitude of the various categories of risk as objectively as possible. The present state of the analysis of health risks is rather heterogeneous. This paper identifies and discusses the most significant issues concerning the present status of risk analysis for energy systems. Such issues include the specification of the boundaries which define the fuel cycles to be analyzed and the formulation of a rational basis for their comparison. For meaningful comparisons to be possible, health detriments which are valued differently must be carefully distinguished and not aggregated artificially into some synthetic risk indicators. Rare but severe accidents must, for the same reason, be considered separately. Policy decisions which always imply value judgements as to the relative weight to be given to the various categories of risk are possible only on this basis.

Most health risks of the conventional fuel systems and for nuclear energy have a relatively sound statistical basis. A main problem is the determination of the health risks of atmospheric pollution to the public. For most renewable energy systems, risk analysis is still at an early stage of development.

1. INTRODUCTION

In the years 1987-88 the author undertook a critical review of the world-wide literature on the health risks incurred by the various options for the production of electrical energy, the aim being to assemble information which would allow inter-system comparisons of the risks of large-scale plants which could be built today under typical Central European conditions.

This work was performed in connection with a series of energy scenarios which were requested by the Swiss parliament to illustrate the possibility, prerequisites and consequences of a withdrawal from the production of nuclear energy in Switzerland, this as background material for a possible future decision in this sense [1]. The main results of this study have been published [2, 3] and shall not be addressed further here. This work and the perusal of the relevant literature over many years have given the author the opportunity to gain some insight into the development and the present state of the art of energy risk analysis and into its methodological and practical problems. Some comments on these problems form the theme of this paper.

The scope is limited to the *health risks* of electrical energy production. Clearly there are many other negative consequences connected with one or other, or with all options for the production of energy which any policy decision in this area will have to take into account. Of these, *environmental impacts* are of particular relevance today. A large part of such environmental impacts are, however, a result of the emission of noxious substances in the course of the realization of any energy cycle, and they are thus covered at least indirectly in what follows.

The aim of energy risk analysis is to determine the magnitude of the various categories of risk as objectively as possible. In the majority of instances, such risk figures are based directly or indirectly on the statistical-actuarial processing of our experience as to the frequency of accidents, injuries, illnesses and fatalities in the many situations encountered by workers and the public during the course of the production of energy. Clearly, however, decisions with *subjective elements* play a role even in judging whether a certain statistic is appropriate to the specific situation of interest, while subjective decisions are unavoidable when the original data, e.g. emission rates, must be converted to health detriments or if the frequency of rare events must be synthesized with the help of basic statistical information on the reliability of components and models of the systems concerned. It is obviously necessary that such decisions and the rationale behind them are fully documented. In much of the past literature in this field, such documentation leaves much to be desired.

In view of the fact that many of these subjective decisions are up to a point rather arbitrary, normative international agreement such as that on the recommendations made by the International Commission on Radiological Protection (ICRP) in the field of ionizing radiation would simplify both energy risk analysis as such, as well as the comparison of the results of such endeavours.

2. FUEL CYCLE BOUNDARY DEFINITION

It is by now axiomatic in the risk assessment field that the risks associated with the production of energy are composed of the sum of the risks resulting from all steps forming a part of the *whole energy cycle* concerned. This cycle normally begins with the procurement of the fuel, continues with its transformation into directly useable form, reaches its climax, so to speak, with the energy conversion process, to end with the final disposal of all wastes produced. In the early days,this was not or could not yet be put into practice as systematically as later, so that the results of many early risk estimates are of little relevance today.

Probably the first person to attempt an assessment of the health risks of the regenerative energy systems, H. Inhaber, in a study [4] which (rightly) raised violent criticism for quite other reasons, was also the first to draw attention to the fact that the risks relating to the construction of all plants used in an energy cycle, together with the risks incurred by the production of all raw materials needed, must properly also be charged to the energy produced. More recent work aims to include also these risk components, but this is not always done with the consistency one should expect.

This line of argument is logical and the *definition of the boundary* of a fuel cycle on this basis appears straightforward. But this is hardly the case. If the risks of producing all raw materials are included, should this also include the risks of mining the iron ore? And what about the risks incurred in the construction of the factories to make the steel? All these preliminary steps require energy. Must the risks of producing this energy also be included? And how about the accidents to which the workers are subject on their way to work?

One could go on and on in this way. True, the relative magnitude of the risk stemming from such preparatory activities tends to become smaller and smaller the further one gets from the main line of the energy production process. But this is specific to a particular fuel cycle, so that the importance of certain of these elements will be rather different for the fossil fuel and nuclear cycles with their high flux energy conversion on the one hand and for the material intensive, low energy flux solar and wind cycles on the other. Another case in point is the enrichment of uranium. The energy requirements per unit of separative work are around 20 times higher for enrichment by the diffusion and the jet process (Trenndüse) than by the centrifuge process [5], so that the proportion of electricity production risks is not necessarily negligible in the first case.

In addition, there is some discussion among risk analysts whether gross risks or rather net risks should be determined. The latter take into account a possible restructuring of the economy due to the additional materials requirements postulated on the basis of an Input-Output-Analysis. Questions can also be raised of the kind, whether the steel used to build a particular plant would not have been produced in any case. If the amounts of materials required are small relative to the total production, then no problem should arise. However, the glass requirements in a large solar energy based economy could easily be of the same order of magnitude as present production capacity, so that the corresponding economy would undoubtedly be influenced.

These few indications have shown that one can get into very complex arguments if one attempts to be strictly logical and precise. In the interests of simplicity and practicality it would seem to be necessary to agree pragmatically on some artificial boundaries, even if these are, in the final analysis, somewhat arbitrary. The definition of such boundaries would be a worth-while effort within the framework of an international discussion of a suitable format for energy risk analysis.

3. CHOICE AND COMPARABILITY OF ENERGY SYSTEMS

The choice of the type of energy systems to be assessed will usually be determined by the aims of the study. However, to enable a risk assessment to be performed, plants with specific technical characteristics must be postulated, and here a further set of problems can arise.

It would generally seem reasonable to define plants on the basis of *present day technology*. This would seem to guarantee comparability, for the risks of old plants will always be higher than those of corresponding new ones. But this does not necessarily mean that these comparisons will also be valid in the future, after plants have undergone further development, and such comparisons are often undertaken with the future in mind. It is unlikely that the conventional fossil fuel systems will see major risk reducing development, but most of the new renewable energy systems are still in an early development stage. Their technology is likely to experience very considerable improvement in the coming decades and in fact must do so if these systems are to become economically competitive. How can the risk reduction potential of such unforeseeable developments be guessed at today? In the light of this argument, present day estimates of the risks of fusion energy, whose practical feasibility even has not yet been demonstrated, can hardly command much confidence.

It is clearly necessary to compare the risks of energy systems on the basis of the *same kind and equal quantities of useful produced.* A comparison of risks due to the production of electrical energy on the one hand with those due to the production of heat for domestic or industrial purposes or with energy for transportation on the other is out of the question. Thus the risks must be related to a specific quantity of energy in the appropriate end-use form, or to a measure directly related to this: for electricity say 1 gigawatt-year electrical, for heat energy perhaps the heating needs of 1 million houses per year or for transportation 1 billion passenger kilometres or miles.

Focussing now on the apparently simple case of electrical energy, a first problem arises from the fact that materials and labour requirements, and thus the corresponding risks,as well as the costs,vary inversely with *plant size.* For conventional fossil fuel and nuclear power product:ion, large centralized plants of a few 100 MW to about 1000 MW capacity are the rule. But lately, at least in European countries, there is much discussion of smaller decentralized power plants, both for the single-purpose production of electricity as well as for combined heat and electricity production. Individual photovoltaic solar and wind energy systems, however, have as yet not been and will usually never be built in anything like this size. On the other hand there is, from a technical point of view, no lower limit to the plant size of these systems with respect to their capability to produce and feed electricity into a grid. Extreme differences in plant sizes will certainly distort any comparison of energy production risks.

But that is not all. No energy system can produce electricity continually, without interruption. Such interruptions can be due to purely technical reasons. No machine functions without occasional component failures or other disturbances which call for a cessation of operation. And every machine requires maintenance at regular intervals. Fossil thermal power plants generally have load factors around 60-70%, modern nuclear power plants achieve 75-85% and above. Thus one single plant will never be in a position alone to satisfy an uninterrupted energy need. In a large electricity grid such *non-availability* is easily compensated for, particularly in view of the fact that much of the shut-down time can be programmed beforehand. Nevertheless, it remains a fact that any single energy production plant has to count on the availability of a source of ***back-up energy*** during the time that it is inoperable.

The new renewable systems which utilize the energy of the sun and the wind are a special case. The sun shines only during the daytime – if at all – and the wind also is very dependent on weather conditions, so that in general the load factors of such energy systems are far lower than the figures mentioned above for conventional plants. Because other production units of the same kind are no help in this case, it becomes somewhat more difficult to define a clear basis for comparison with other systems.

It is generally agreed that the inevitable day-to-night variations must be compensated by the provision of appropriate *energy storage* facilities and that the corresponding risks of construction, operation and maintenance of such facilities must be charged to the energy produced. However, during more extended periods of nonproduction due to cloudy skies or lack of a minimal wind speed, these systems must rely on other energy supply facilities. Here the discussion is quite open as to how the necessary back-up energy should be produced and to what extent the corresponding risks should be charged to the renewable energy system concerned. The concrete solution chosen can depend strongly on the character of the national energy supply system, so that it might be rather more difficult to solve this problem by means of a normative decision. Problems of the non-equivalence of energy quality also crop up in the utilization of hydraulic energy from storage and from run-of-the-river plants insofar as the risks of these plants are determined individually.

Another aspect which arises in the determination of the risks of energy production and which has, to the author's knowledge, only been addressed in some of the latest work, is the fact that quite a few of the *boundary conditions* can *vary* substantially *from country to country*, or at least from one part of the world to another. This problem must be kept in mind in particular by an international organization presenting numerical figures in this field.

As an example it may be mentioned that the risk of fatal accidents of the workers in coal mines appear on the average to be twice as high in West German mines than on the average in mines in the United Kingdom and United States of America, and this risk is considerably higher still in Eastern Europe, in China and in developing countries.

A major part of the health risks to the population results from the emission of noxious substances during the production of base materials or the operation of the power stations. The extent of the social health detriment is directly proportional to the specific emission rate of such substances and to the size of the population affected, i.e. to the population density around the plant. The regulation of these emission rates, however, varies from country to country, as do the population densities. The risks resulting from the transportation of fuel, materials and wastes can vary considerably depending on the mode and distance of transport, both of which are determined by country specific conditions. And as a final example: the specific power production of a solar plant situated in Arizona is of little relevance to solar electricity production in most parts of Europe.

Many risks, on the other hand, vary little regionally, though even general accident statistics often show non-negligible variations, presumably at least partly due to differences in category definitions. In the strict sense, then, there are no universally valid risk figures. A risk analyst will have to become clear in his mind in which geographical frame his assessments are to be performed, taking into account, among other things, that perhaps not all stages of a fuel cycle will or can be realized in one and the same country. For example, Switzerland and France import all or much of their coal from very diverse parts of the world.

An organization attempting the presentation of more generally applicable risk figures has the choice of two solutions. The range of risks quoted can, on the one hand, include the full scope of individual risk values in each specific category, from the lowest to the highest values found. This will in many cases lead to results which, because of their imprecision, can be of little use for policy decisions. On the other hand, risks can be determined for clearly specified regions, which have some similarity in the relevant boundary conditions, such as North America or Western Europe, and the full range of risks then quoted for these regions. In the past, a major part of the energy risk analyses were performed in the US, more or less in agreement with the second approach, but the risk figures obtained were not always relevant for, say, Western European conditions. Reviews presented by international organizations have in many cases been quite a hotchpotch of figures from the most diverse sources.

As the methods and practice of energy risk assessment have improved, it becomes increasingly necessary – as well as possible – to account for the more important systematic regional differences and thus to obtain more precise and correspondingly more useful risk figures, at least for the more conventional energy systems.

4. HEALTH DETRIMENTS AND THE POSSIBILITY OF THEIR AGGREGATION

Even if one limits a risk analysis to health risks, a whole list of *risk categories* must, in principle, be considered. A wide range of injuries due to accidents and illnesses can occur in the course of the many processes involved in energy production, beginning with those of a trifling nature up to events leading to invalidity or premature death. It is obviously difficult to define unequivocal limits for classes of injuries and illnesses of different seriousness and even to define a cut-off below which such health effects shall not be considered, and which will be interpreted in the same way by everyone concerned. Thus, statistics of accidents and of non-lethal *injuries and illnesses* are notoriously incomplete and unreliable and, where available, hardly comparable from case to case. In the author's opinion they are of little use for risk comparisons for this reason. In the early days of risk analysis, figures for the frequency of injuries were not infrequently derived from fatality statistics by the application of a more or less arbitrarily determined factor – obviously a futile undertaking.

Thus, health risk analysts are usually limited to the determination of the risk of *premature death*. In the sense that death is unambiguous, fatality statistics are likely to be complete and thus reliable, perhaps with a certain proviso in the case of death through illness due to possible uncertainty in the diagnosis. On the one hand this is a considerable restriction within the wide spectrum of health detriments, but nevertheless a restriction to that form of harm which is generally judged to be the most serious. In any case, like the tip of an iceberg, the frequency or risk of death is usually quite a good indicator of where the major health risks occur.

In addition to the possibility of immediate death, either due to an accident or an acute disease, ionizing radiation and chemical pollutants can have effects leading to *delayed death*. Of particular significance is the possible occurrence of cancer, either after a latency period of some decades following an acute exposure or after an extended period of chronic exposure. The assessment of such delayed risks forms an important part of energy risk analysis.

The agents mentioned, radiation and pollution, finally can also lead to *teratogenic* and/or mutagenic or *genetic damage*, that is, to impaired development of an unborn child or to damage to the descendants of the exposed person. Considerable information is available on both of these potential consequences in the case of exposure to ionizing radiation, our knowledge in the case of the many chemical pollutants of relevance in energy production, however, is extremely limited or practically nonexistent. For this reason, few attempts have been made to estimate the corresponding risks.

The risk analyst must, of course, determine the magnitude of these very different potential health detriments one by one. He is now confronted with the problem as to what extent should he keep these risk categories separate from each other in the final presentation of his results and what *possibilities for their aggregation* into combined categories he can afford to employ. He will have to explain these results, not in the first place to specialists like himself, but rather to laymen such as the politicians and policy makers will usually be. Here any condensation of the quite intricate and extensive information would be welcome. On the other hand, however, it is well known that the layman perceives the various categories of risk very differently [6]. Death as a result of an accident and a late death are felt to be of quite different quality. An accident at work is judged as something wholly different from an accident to an uninvolved bystander.

In the author's experience, aggregation of such different categories of harm jeopardizes any meaningful communication with the layman and should therefore not be undertaken. Nevertheless, acute fatalities among workers, whether these occur in a coal mine, during transport operations or during the operation of a power plant can fairly be referred to one and the same category, just as late cancer fatalities among the general public can form another category of harm, whether these are predicted as the consequence of radiation exposure or of exposure to chemical pollution. In this line of thought, then, the following categories should be distinguished:

Persons at risk:	occupational	public
Cause of harm:	accident	disease
(occurrence:	immediate	delayed)

which in combination lead to four separate categories of harm.

In early risk assessments the aggregation of consequences to health was demonstrably excessive. Immediate and delayed fatalities were frequently simply summed up, as were fatalities among occupational personnel and the public. More and more the view has come to prevail that this cannot be defended and that it is, in the final analysis, counterproductive. A comparison of the health risks of energy systems should be performed category by category, leaving it to a *final overall judgement* to bring these individual consequences together. It should here be stressed that this overall judgement is by no means a purely professional matter but rather a *uniquely sociopolitical* one, implying as it does a whole series of value judgements which must weight the various categories of harm one against the other.

It is to be deplored that even in some recent work [5] this principle is not yet accepted, acute and late fatalities being treated as one single category. Another habit, frequently practiced even today, mainly in the USA, is to aggregate injuries and fatalities into a measure: 'Worker Days Lost' (WDL) or 'Man Days Lost' (MDL), where one fatality is equated usually to 6000 days lost. The author feels this should be avoided, not only for the reasons of principle just discussed, but also in view of the general untrustworthiness of injury statistics.

A category of risks which should be clearly set apart from those risks which can be determined on the basis of actuarial evidence are the *risks of delayed harm*, particularly cancer, as a result of radiation or chemical pollution. The fatalities determined in the former group are deaths which have actually occurred and which will, in a statistical sense, occur again in the future with the frequency ascertained.

The second group comprises fatalities which have to be calculated on the basis of a theoretical dose-effect relationship. Such a relationship extrapolates the extent of harm which has been determined at high doses down to doses frequently many orders of magnitude lower. At such low doses it is not possible to demonstrate any harm experimentally or epidemiologically, because the harm in question – cancer – is unspecific, that is, can have many causes, most of them unknown, which cannot be separated from the agent considered. In fact, then, in this case the risk of harm is based on a hypothesis; it can be just as likely that there is no harm whatsoever, at least at very low doses.

In the case of *ionizing radiation*, there is world-wide agreement on the assumption of a linear dose-effect relationship, without a threshold, down to zero dose. This postulates that there is no harm only at zero dose. It is agreed that in most cases this hypothesis is conservative, i.e. that it overestimates the harm.

Our knowledge of the harmful effects of the many kinds of *chemical pollutants* emitted in the framework of the various energy cycles is far more rudimentary than of those due to radiation. In practice, the problem is simplified by taking SO_2, sulphates or either of these together with particulates as an indicator of the complex mixture of noxious substances emitted. Clearly, this is a very rough approximation when One considers how varied the composition of the emissions can be. Epidemiological studies to determine dose-effect relationships are even more difficult here than in the case of radiation. In the past 20 years at least 30 reviews of the mass of literature in this field have appeared, with quite diverse recommendations.

Though the existence of a dose threshold below which no harm occurs is very occasionally postulated, here too a no-threshold dose-effect relation is almost universally assumed. This again is a conservative assumption, but one which seems all the more justified by the fact that there is, in contrast to radiation, no natural background dose level for most of these pollutants, but at the same time already a by no means negligible non-natural pre-exposure of the population. In any case it appears judicious to postulate essentially similar hypotheses as a basis for comparisons of the risks of nuclear and fossil fuel energy systems. One wonders whether there is room here for a discussion among specialists with the tentative aim of agreeing on a dose-effect relationship as a working hypothesis for health risk comparisons, just as there is presently universal agreement on the use of a linear, no-threshold hypothesis for the effects of radiation?

There are many other questions which the determination of health risks can raise. Only a selection of these can be no more than mentioned here.

With respect to the dose-effect hypothesis for *radiation* just cited, it must be recalled that the *risk coefficient*, i.e. the slope of the linear dose-effect curve, is presently under review since the Hiroshima-Nagasaki data have been reevaluated on the basis of a revision of the dosimetry used hitherto. It is expected that the best estimate of the risk coefficient may be increased by the appropriate international organizations by a factor of between 3 and 5 in the near future. This will increase the assessed hypothetical radiation risks proportionally.

The radiation risks to the public are themselves the result of calculations of the propagation of the radioactive substances which are emitted from the plant being analyzed and their distribution among the population in the vicinity, the doses which thus arise being transformed to harm by the application of the dose effect relation. Because radioactive substances have very different half-lives, the question arises as to the *extent of the temporal* as well as the *spacial integration* of their harmful effects.

On the basis of a no-threshold dose-effect relation;the integrated harm can become quite considerable even if doses are extremely low, if this integration is performed over a very extended region or over a very long time period - a case of multiplying a very small value with a very large one. Thus the consequences of the emissions of long-lived carbon-14 from the nuclear fuel cycle have been calculated on a global basis and up to a period of 10 000 years (UNSCEAR, 1982). In a special context this may perhaps have some meaning, but for purposes of comparison of nuclear with other risks it would be quite unreasonable. Rather, one would need to give the concept of a *de minimis dose*[1] some consideration, that is, the normative definition of a very low dose, below which effects are taken to be so small, that they can be disregarded. This implies the integration of harm over a limited distance and a limited time period, both of which would need to be fixed by general professional consensus.

Another point at least worth mentioning is the fact that premature death from some causes can systematically occur only relatively late in life, thus being responsible on the average for considerably less *shortening of life* than that due, say, to a transport accident, which can happen to a person of almost any age. This again is a difference in the quality of the corresponding risks, which has not, as yet, been specifically considered in risk comparisons.

A final point concerns the significance of late health effects quite generally, best illustrated by the incidence of pneumoconiosis (black lung disease) under miners. This disease can lead to death through progressive massive fibrosis (PMF), but only after something like 30 years. The present day statistical incidence of such fatalities is thus a picture of the conditions in the mines during the last 30 or more years. Which risk of PMF fatalities should one now take into account; the incidence rate presently effective or the rate expected under the improved conditions existing in today's mines?

5. THE PROBLEM OF SEVERE ACCIDENTS

A category of risks with very special characteristics results from the possibility of a very severe, though very unlikely accident of a technical system. The very low probability of such an event means that there has been little experience of their occurrence, particularly during the operation of new technological systems. Nuclear power plants are a case in point. Here the problem of quantifying the risks has been solved by the introduction and systematic development of *probabilistic risk or safety analysis* (PRA, PSA). Though PRA, in the final analysis, also draws heavily on statistically assembled experience of failure rates of system

[1] "de minimis non curat lex". Legal principle: The law does not bother with trifles.

components and operating personnel, the results obtained have a character and significance different from those of purely statistically determined risks, which.must not be forgotten when comparing risk figures.

The most striking aspect of severe accidents, which became manifest most noticeably after the publication of the first results of a PRA by Prof. N. Rasmussen in the USA, is the most fundamental difficulty which the average citizen seems to have in the *perception of a low probability event.* From the basically objective point of view of the risk analyst, the risks incurred by a severe accident are, as in every other situation, a function of the magnitude of the possible harm and of the probability that this harm will materialize. Here, both the harm and the corresponding probability can vary, usually over a wide range. Purely from a mathematical point of view one can determine an average risk, the so-called *expected value.* This figure is, even from an objective point of view, not quite satisfactory, because it treats an event with a probability of 1 in 100 per year causing 10 000 simultaneous deaths as equivalent to an event causing 100 deaths regularly every year, one at a time. Clearly, the consequences for society of 10 000 deaths all at one time are in many ways more difficult to overcome than those of the same number of deaths occurring one by one.

What, however, sets severe accidents completely apart from all other categories of risk is the *subjective perception* of such an event by the man on the street [6]. The harm caused by such an accident, usually graphically described by the media, can be impressive and fear provoking, and dominates his valuation of the event. The second element of the risk, the low probability, he demonstrably misperceives, usually by many orders of magnitude. The great popularity of lotteries, where the chance of winning the main prize is often in the order of 1 in a million, is a typical expression of this.

This widespread misperception of low probability severe accidents is the reason why this type of risk must also be dealt with as a separate category, here also further differentiated according to the four categories listed on page 7. These cannot be compared directly with the other risk categories discussed previously. A final estimation again implies value judgements, which must be made quite independently of the objective risk determination. For this reason, all attempts, repeated again and again, to account for the subjective overemphasis.of the harm by defining some new sort of 'severe accident risk' as probability times an overlinear function, often an exponential function of harm, are totally misguided. The subjective and frequently highly emotional valuation of certain risks must be considered within the framework of a socioeconomic process and must be kept quite apart from the objective determination of the numerical value of risks.

In view of the enormous attention paid in the public to the possibility of a severe accident in a nuclear power plant,at least since the events at Three Mile Island and in Chernobyl occurred, it is quite surprising that the occurrence of *severe accidents in the frame of other energy cycles* are hardly taken note of. Of course, if at all, such events are usually reported by the media in only a few sentences. As a matter of fact, such events are so frequent that quite meaningful statistics exist on a world-wide basis. During the last 20 years over 200 workers lost their lives in coal mine disasters on the average every year. The average loss of life in the oil energy cycle due to capsizing oil platforms, fires and explosions in refineries, tank farms and during transport was over 100 per year, in the natural gas cycle almost as many. Hydraulic dam disasters accounted for an average of over 200 deaths per year.

It is incomprehensible to the author why the risks of severe accidents in the non-nuclear energy fields have to this day not been analyzed. The statistical material needed, namely the corresponding accident and energy production statistics, is available. This is by far the most serious omission in 20 years of energy risk analysis, and it should be corrected as soon as possible.

6. CONCLUDING REMARKS

The present status of energy risk analysis is rather heterogeneous. In all areas, more detailed statistical data on labour requirements and accident frequencies would be welcome. But global accident statistics are not always sufficient in some trades, where risks in different fields of work can differ considerably. Thus the general statistics for the building trade are inappropriate for the determination of the occupational risks during the construction of large hydraulic dams, where working conditions are considerably more dangerous than on average building sites, particularly in alpine regions.

Most risks of the *conventional fuel systems* have quite a good statistical basis. The main problem here concerns the determination of the health risks of atmospheric pollution, which has already been mentioned. Risk figures for *nuclear energy production* on the basis of the light water reactor cycle are rather well documented. Other nuclear cycles, such as those based on the high temperature reactor or the fast reactor, call for considerably more work, while it is probably premature to present risk estimates for fusion energy.

The state of the art of risk analysis for most *renewable energy systems* still leaves much to be desired. Many of the problems here have also been discussed. Risk analyses should be performed hand in hand with the further development of these energy systems, but it will be some time before well-founded risk figures will be available permitting final conclusions relative to the other energy systems. Figures for the risks of hydraulic energy production are still rather unsatisfactory, but one feels that much basic data must be available which is waiting for appropriate processing.

The long-range aim of energy risk analyses might be to obtain risk figures accurate within about a factor of two. In a few areas this goal has now probably been reached, but in others much work remains to be done, while in fields such as the health risks due to noxious emissions this stage is never likely to be reached.

Of the scatter which one finds between the figures of different risk assessments, one must be aware of the fact that probably the larger fraction is due to the countless possible real differences in the specific details of the energy cycles studied, while only part is due to actual uncertainty of individual figures. As everyone active in this field knows, however, risks which are to be compared very often differ by far more than factors of two, in many cases differences will be one or more orders of magnitude.

In such a situation quite unequivocal conclusions can be drawn even from the results of many of today's risk analyses.

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Background Papers to

INCORPORATION OF ENVIRONMENTAL AND HEALTH IMPACTS INTO POLICY, PLANNING AND DECISION MAKING FOR THE ELECTRICITY SECTOR

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NUCLEAR ELECTRICITY IN FRANCE: ASSESSING ITS IMPACTS ON THE ECONOMY AND THE ENVIRONMENT THROUGH AN INTEGRATED MODEL

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ABSTRACT: This paper summarizes an attempt to assess the economic and environmental impacts of the French nuclear programme. It is based on the results of a simulation achieved with MELODY, a macroeconomic model which describes in detail the energy sector. The comparison is made between the actual French energy strategy and an alternative strategy where the series of PWR-900 units is replaced by coal fired power plants. It is shown that the coal strategy would have entailed a lower GDP growth rate, an increase in the deficit of the balance of payments and a large increase in the polluting atmospheric emissions.

1. INTRODUCTION

Because of the thinning of the ozone layer, the greenhouse effect, global warming and acid rains, national and international authorities are under mounting pressure from the public to ensure that economic development must be environmentally sound.

Thus, developing countries are pressing the United Nations to contribute to global cleanup schemes. At the same time, the European Communities are struggling to introduce new controls on polluters, ahead of the economic boom expected to come after trade barriers come down in 1992.

National authorities also try to limit pollution and promote sustainable, environmentally friendly development. Many measures could be thought of: new environmental standards and more controls, taxes on fossil fuels, tradeable permits for toxic waste producers, investments to cut down emissions of sulphur dioxide, etc. Moreover, in France, a so-called 'environmental impact assessment' is now an essential prerequisite for every programme, especially in the industrial and energy sectors.

More often than not, environmental questions are external to microeconomic choices. For example, lack of environmental standards and few controls could be a major attraction for some Western operators to invest in the East. Thus, the governments must commit themselves, since national authorities are concerned by the assessment, choice, and implementation of energy policies incorporating environmental concerns.

Commonly, information provided by technical analysis could be used to set up decisions: 'ecological efficiency' of an energy process and its associated cost, return from investments in environmental protection measures, etc.

However, little information is available to get a value indicator of the environmental benefits. Recent methodological developments in the economic field provide valuation methods for various environmental services that are provided by natural goods outside the market. However, these theoretical methods, based on a micro-economic analysis of the marginal opportunity cost, are seldom applied because of their complexity. Moreover, when an 'ecological policy' is initiated by the Government, assessment could be carried out only on a macroeconomic level, for reasons summarized below.

First, because those who carry the burden of the changes are not always those who get the benefits and those who pay. So that, e.g., consumers could have to bear the brunt (or part of it) of new charges on farmers using non-biodegradable fertilizers. This is a major feature, because the economic transfer among national actors, and even across boundaries, could occur through the price structure. **Secondly**, because microeconomic efficiency differs from macroeconomic efficiency. Energy consumption could be highly modified by economic changes, so that price effects or income mechanisms could strengthen the ecological efficiency of the technical process. **Thirdly**, because the government must assess its policy on a global basis. Macroeconomic impacts, including economic activity, employment, inflation, international trade, etc., should be evaluated in a sound and reliable way. **Fourthly**, because environmental issues are of a worldwide nature, and facing these may thus imply international actions such as the setting of worldwide ecological standards, and sometimes aid packages.

Currently, the suitability of ecological schemes cannot be assessed clearly because the environmental benefits can hardly be evaluated. On the other hand, we highlight that the implementation of environmental reforms is not a trivial matter. This is why macroeconomic models are so attractive to deal with these problems.

Experts of the European Communities are already following this line as Hermes econometric models were used for environmental purposes in 1989. The French Atomic Energy Commission (CEA) is engaged in similar studies, focussing on the assessment of the French nuclear power programme.

Before getting to the heart of the matter, which means an example of quantitative macroeconomic assessment, let us come back to the tool. In MELODY-FRANCE economic modelling has been adapted to energy planning purposes, from technical process description to the extension of the running period, as a prerequisite to obtain a relevant assessment of the French energy policy.

2. THE MELODY MODEL

The main specifications of MELODY are shown in Fig. 1.a; and a simplified description of the model is given in Fig. 1.b.

MELODY is a long-term model, because energy problems imply long-term assessments. Indeed, the lifetime of equipment for producing or using energy, and the lead times for their implementation, are quite long. For a nuclear power plant, e.g., the construction lead time is about 10 years and the operating lifetime is more than 30 years

MELODY gives a complete description of the French economy but the methodology used can be adapted to other countries. The models built for Algeria, Morocco, Jordan and Tunisia are examples of such an adaptation. It should be noted that building a model adapted to measure energy/economy interaction needs a complete description of, first, the major rôle that prices play in the economy and, secondly, of the structure of the production and the consumption of energy.

The model includes three producing sectors (electricity, fossil fuels and non-energy products) but for the purpose of energy studies, especially in the electricity field, the fossil fuel sector has been highly disaggregated. Hence, inputs of solid fuels, crude oil, petroleum products and the whole nuclear cycle (uranium extraction, enrichment, fuel fabrication and reprocessing) were described separately.

In Fig. 1.b., this level of disaggregation does not appear since all the equations of the model describing the technologies of these sectors are included in the 'SUPPLY' box.

For the non-energy products sector, output prices and demand factor prices are computed as functions of relative prices of inputs: capital, labor, energy and non-energy intermediate consumption, and substitutions between energy and non-energy inputs are analyzed. It is an important feature of MELODY which allows the assessment of macroeconomic impacts of the French nuclear programme induced by the changes in electricity generating cost and the associated price variations.

For the energy sectors, the production is described in the model in a somewhat different way, as shown in Fig. 2. The production of electricity is described from a technical point of view. The management of the generating capacity is performed by pooling the different power plants under the load duration curve, itself fitted on the basis of the sectorial demand of electricity. Moreover, the model computes the quantities of inputs needed to produce electricity (labor, materials, fuels) and builds the whole account of the French utility (Electricite de France, EDF), including funding and debt services. This result then allows to evaluate the adequate average selling price of electricity.

For the other energy sectors, the technology is described through exogenous input-output coefficients.

The box 'USER PRICES' of Fig. 1.b includes econometric equations for computing the final user prices (household consumption prices, government consumption prices and export prices), the price of investment and the price of labour. The price of output and the foreign price index are used as leading prices in these equations, where user prices are mainly increased by the indirect tax rates. Hence, the model allows to measure the macroeconomic impacts of a new taxation policy corresponding, for example, to a new energy pricing policy.

The box 'FINAL DEMAND' of Fig. 1.b includes mainly econometric equations of household behaviour and investment. The link between the 'FINAL DEMAND' and the 'SUPPLY' boxes comes mainly from the total household income, which is, together with the relative prices of goods, an independent variable in the final household consumption equations. Indeed, the main component of household income is wages, depending on labour demand by the producers. Finally, the relative price of capital plays a major rôle in investment decisions.

Figure 2 shows another important specification of the model. Econometric equations for exports and imports allow to take into account the rôle of external trade in the economy. Imports and exports depend mainly on a competitiveness index which is built up from domestic prices, foreign prices and exchange rate evolutions. A foreign demand index is also used as an independent variable in the export equation. Hence, the competitiveness between domestic and imported energy is not ignored by the model.

As shown in Fig. 2, the model includes two main parts, a price loop and an income loop. The price loop is described in Fig. 3. Tax rates and foreign prices are exogenous. For a given level of input prices, capital, labour and intermediate consumption prices, the output price level results from the producer decisions. This price in turn plays a rôle in the evolution of the prices of the factors and again in the output price growth. Then, the rate of inflation in the economy is directly linked to the evolution of the purchasing power of wages. This loop shows how, for instance, an energy price increase can play an important rôle in the economy. It modifies the production costs and consequently the production structure. The final uses of each product are also affected through the output price change.

The income loop corresponds to the Keynesian multiplier and is described in Fig. 4. If investment increases in the energy sector, it induces an increasing requirement for goods, that is, of production. Additional investments and labour are then necessary to meet the requirements. The increment of labour induces an increase in the household income. The additional income is partly saved and partly consumed, inducing an additional growth of the final demand. Since this process is iterative, the supply of goods must increase again, leading to a new final demand, and so on. The Keynesian loop plays an important rôle in the present analysis because investments in the energy sector are higher when electricity is generated by nuclear power plants rather than by coal fired plants.

The price loop and the income loop are, of course, running together in the model. The primary link between these loops is made by the equations determining the household consumption where the income, but also the prices, are dependent variables. In addition, it should be noted that the long-term evolution of the endogenous variables depends mainly on the structure of prices. The income loop determines only the short and medium term evolutions. This is a characteristic of long-term models, where prices are leading variables.

The model allows also to compute polluting emissions such as nitrous oxides, sulphur dioxide and carbon dioxide. These emissions depend on the type of fuel used and sometimes on the technology adopted, especially in the case of electricity generation. The result given by the model is a complete air pollution balance of the country. Such an evaluation is of utmost importance in the assessment of the environmental impacts of energy policies.

3. ASSESSMENT OF THE FRENCH NUCLEAR PROGRAMME

3.1. Description of the alternative scenario to nuclear

In order to evaluate the macroeconomic impacts of the French nuclear programme with the MELODY model, a case study was carried out based on the assumption that the alternative scenario would have been to build coal fired power plants. In this alternative scenario, only the PWR-900 units constructed between 1970 and 1980 and due to be decommissioned before 2015, are replaced by coal fired power plants.

The goal of the study is to measure the economic and environmental impacts of an alternative electricity generating system over the entire lifetime of the facilities. As the running period of the MELODY model ends in 2015, it is not possible to include in the analysis the PWR-1300 units and the PWR-1400 units, which will still be in operation after 2015. Figs. 5 and 6 give the share of the various fuels in the French electricity generation between 1970 and 2015 for the reference scenario and the coal scenarios, respectively.

In the coal scenario, the 34 PWR-900 units are replaced by coal fired plants of roughly the same size, 900 MWe, equipped with scrubbers for desulfurization to reduce the SO_2 emissions. However, four units of 600 MWe, built in Lorraine and using the regional coal which has a low sulfur contents, do not necessitate desulfurization equipment. Except for these four units, the average investment cost for the coal fired power plants is 9% higher than in the reference scenario. Although the economies of scale and size effects tend to decrease the cost of coal fired power plants in the coal scenario, the need for desulfurization associated with large deployment of coal burning facilities leads to an overall increase of the costs per unit of capacity installed.

3.2. Impacts on the required investments

The choice of coal instead of nuclear for the power plants built in the seventies and early eighties would have entailed postponing the investment needed in the nuclear industry for providing NSSS, other nuclear power plant equipment and fuel cycle services.

Regarding the power plant construction industry, however, the investment required is about the same for coal fired plants as for nuclear plants, per unit of electricity generating capacity to be installed.

The construction cost adopted for coal fired plants is based on data provided by the French Ministry of Industry, and takes into account the desulfurization, the size of the units, the series effect, and the incremental costs associated with the need to find more sites adapted to large coal-burning facilities.

The coal scenario entails a postponement of most of the investments in the nuclear fuel cycle industry, and a reduction of the cumulated investments in this sector, because some plants would not have been needed if the nuclear programme had been limited to the PWR-1300 and PWR-1400 units. The enrichment plant has its capacity reduced by 25% compared to the nuclear scenario, and the uranium production center of Lodève is not opened before 2015. These reductions reflect a decrease in the installed nuclear capacity and thus in the domestic requirements for uranium and enrichment services.

The coal fuel cycle is less capital-intensive than the nuclear fuel cycle. Nevertheless, the coal scenario requests additional investments in the mining sector and in the importing facilities (harbours). Moreover, the concern for security of supply which was high in the seventies, could have led France to build its own fleet of coal tankers if coal had been chosen as a major contributor to the energy balance. A fleet of some hundred tankers of 80,000 metric tons each would have been needed.

According to these assumptions, the investments required in the two scenarios, for the same generating capacity, differ by less than 10%, if the coal scenario includes tankers, and by some 30% without tankers in the coal scenario, as shown in the following table.

Table I. Cumulated Investments for Implementing a Coal or Nuclear generating Capacity of 28 GW_e (billion French Francs 1984).

	Coal	Nuclear
Power plants	115	154
Coal mines	6	
Harbour facilities	9	
(Tankers)	(43)	
Nuclear fuel cycle	-	38
Uranium mines	-	1.4
Conversion	-	1.1
Enrichment	-	19
Fabrication	-	0.5
Reprocessing	-	16
TOTAL	173 (130)	192

The simulation performed with the model, based on the case without tankers, shows that the reduction of the investments required in the electricity generation sector induced by the coal scenario represents only 0.7% of the gross domestic investment.

The global change in the domestic investment resulting from the coal scenario is broader than the reduction achieved in the electricity supply sector, as induced macroeconomic impacts entail indirect modifications of the investments in other sectors of the economy. However, the direct effect is the most important part of the changes which, in turn, affect the major macroeconomic parameters such as the GDP growth rate or employment.

3.3. Impacts on electricity prices

While analyzing the impacts of the coal scenario on the electricity prices, the global framework of pricing and tariff setting adopted by the French utility EDF has to be taken into account. The pricing policy is based mainly on the Ramsay/Boiteux theory of long-term marginal cost, complemented by constraints reflecting the short- and medium-term concerns. This policy allows EDF to maintain its investment capacity and an adequate level of return from the capital invested. The debt level adds another constraint to the pricing policy leading to a global financial equilibrium.

The prices of coal and oil are influencing factors of the cost of electricity generation and of the competitiveness of electricity. The hypotheses adopted in the present study are derived from data given by French authorities in charge of energy planning; they correspond to moderate tensions in the energy markets, with, for example, a 30% increase in coal prices between 1990 and 2015.

Several electricity price strategies may be adopted to meet the fixed objectives and face the limiting constraints. However, according to model simulations the possible price strategies are pretty close and lead to similar macroeconomic impacts at least in the medium term. Compared to the nuclear scenario, the coal scenario entails a slight decrease of the electricity price until 1980 and an increase of some 25 to 30% of this price between 1980 and 1985; thereafter the electricity price returns progressively to the level corresponding to the nuclear scenario, and remains roughly at that level between 2000 and 2015.

The tariff structure policy allows to differentiate the prices charged to various users according to their cumulated consumption and to variations of their consumption over time. As shown in Figure 7, the industry electricity price is affected more dramatically by the coal scenario than the household electricity price. During the mid-eighties, the average electricity price for industry increases, in the coal scenario, by some 30 to 40%, while the average household electricity price increases by some 20 to 25%. These price increases are key factors leading to a lower demand for electricity and a higher inflation rate which implies worse performance of the economy, because of the decrease of the purchasing power of household incomes.

3.4. Impacts on the electricity and energy demand

The impact on energy demand of such an increase in electricity prices has been assessed using the model simulation. In order to confirm the results obtained by the simulation, two different approaches, a technico-economic study of the fuels, the sectors and the energy uses, and an econometric analysis at a disaggregated level were adopted. The agreement between these approaches is fairly good and leads to the assessments given below for the year 1987, when the impact on energy is the largest.

In the **energy sector**, the decrease in electricity consumption is due to the cancellation of the enrichment plant (about 20 TW·h in 1987), and to the reduction of distribution losses associated with the reduction of electricity transportation (about 5 TW·h). In the **industry sector**, the reduction of the electricity consumption occurs mainly in the heavy industries, such as steel and aluminum production and in the chemical industries. The reduction in this sector is about 13 TW·h in 1987. The electricity demand in the **service sector** is fairly nonelastic to prices and the impact is limited, with a reduction of only 3.4 TW·h in 1987. In the **household sector** the impact is more dramatic, mainly because of the lower deployment of electric heating in dwellings. The total reduction in electricity consumption by this sector was 24 TW·h in 1987, of which 10 TW·h were due to the reduction of demand for heating purposes. In the **agricultural and transportation sectors** the impact of higher electricity prices is negligible.

The electricity exports achieved in the nuclear scenario are not possible in the coal scenario due to the lack of competitiveness. The corresponding reduction in the electricity generation reached some 30 TW·h in 1987, and more than 40 TW·h by the beginning of the 1990s.

Table II shows the changes in the electricity consumption during 1987, resulting from the coal scenario.

Table II. French Electricity Consumption

	Nuclear scenario (TW·h)	Reduction in the coal scenario (TW·h)
Energy	59.2	-25.6
(of which EURODIF)	(20.0)	(-20.0)
Industry	104.5	-13.0
Services	65.4	-3.4
Household	91.4	-24.0
Agriculture	1.6	0
Transportation	6.2	0
Total national consumption	328.3	-66.0
Net exports	29.7	-29.7
TOTAL	358.0	-95.7

On the demand side, this important decrease in electricity consumption induces substitutions mainly by oil and natural gas. The total fossil fuel consumption grows by 6.4 Mtoe, or 3.2%, excluding the coal used for electricity generation.

On the supply side, the coal scenario entails the cancellation of the PWR-900 programme, which means a nuclear electricity generation lower by some 190 TW·h by the late eighties. However, as the demand for electricity is lower than in the nuclear scenario, the additional electricity generation by coal fired power plants amounts only to some 95 TW·h.

Globally, the coal scenario results in an increase of some 37 Mtoe, or 19%, in the French fossil fuel consumption in 1987. This indicates a drastic reduction in the energy independence, from 47% in the nuclear scenario to 27% in the coal scenario.

3.5. Environmental impacts

The coal scenario entails important changes in the polluting gas emissions. For the purpose of the present study, three gases have been considered, CO_2 which is the most important contributor to the greenhouse effect, SO_2 and NO_x, which are responsible for acid rains. A global assessment of the two scenarios has been carried out, taking into account the emissions of the whole energy system. The impacts induced by the reduction of the electricity demand, the substitution of fossil fuels to electricity and the changes occurring in the level of economic activity are considered.

The **direct impact** corresponding to the replacement of nuclear power plants by coalfired power plants is by far the most important one. The emissions from the electricity supply system are calculated by adding to those of the power plants, those of the fuel cycle facilities and those embodied in the investments. The **emissions embodied in the investments** can be derived from an input/output analysis which gives the energy content of the electricity generating plants and their associated fuel cycle facilities. The energy content of a coalfired power plant is about 3,100 thermies per kWe of capacity, of which 800 are imported, while the energy content of a nuclear power plant is of some 5,500 thermies, of which 1,500 are imported. The polluting gas emissions associated with the **fuel cycle facilities** are in both scenarios small compared to the direct emissions of the power plants.

The emissions from coalfired power plants have been evaluated assuming that, in the coal scenario, advanced coal technologies would have been developed and implemented, leading to an efficiency of 40%, instead of 30% in the nuclear scenario. The SO_2 emissions are calculated assuming that desulfurization is achieved by scrubbers, as fluidized-bed technology was not available in the 1970s or early 1980s. A first evaluation of the additional polluting gas emissions associated with the coal scenario is carried out assuming an electricity generation equal to the one experienced in the nuclear scenario, that is to say some 190 TW·h in 1987. The corresponding annual emissions amount to some 200 million metric tons of CO_2, 51,000 metric tons of SO_2 and 435,000 metric tons of NO_x.

However, the actual impact of the coal scenario is modified by the drastic reduction of the electricity demand, as compared to the nuclear scenario, resulting from the higher price of electricity. While in the nuclear scenario the electricity generation was of 190 TW·h in 1987, the demand is only 104 TW·h in the coal scenario. It means that the above evaluation, corresponding to the generation of 190 TW·h, has to be corrected; the CO_2 emissions are lower by 100.6 million metric tons, the SO_2 emissions are lower by 34,000 metric tons and the emissions of NO_x are lower by 219,000 metric tons.

Besides, the high electricity price prevailing in the coal scenario entails substitutions to electricity by direct burning of fossil fuels. These substitutions lead to additional emissions of some 15.7 million metric tons of CO_2, 187,000 metric tons of SO_2 and 556,000 metric tons of NO_x. The slowing down of the economic activity resulting from the coal scenario implementation entails a reduction of the emissions of some 2.7 million metric tons for CO_2, 10,000 metric tons for SO_2 and 16,000 metric tons for NO_x.

Table III summarizes the integrated environmental impacts of the coal scenario, for the year 1987 when the gap between the two scenarios is the largest. As compared with the nuclear scenario, the increase of the emissions reaches some 40% for CO_2, 13% for SO_2 and 15% for NO_x. The coal scenario would have led France to a level of CO_2 emissions per inhabitant close to that of Germany and higher than the levels of Spain, Italy or the United Kingdom.

Figures 8, 9 and 10 give the evolution of the CO_2, SO_2 and NO_x additional emissions resulting from the coal scenario between 1970 and 2015. Three different periods may roughly be identified. A large rise of polluting emissions is experienced between 1980 and 1987, when coalfired power plants are implemented instead of PWR-900 units. Then, between 1990 and 1995, the additional emissions are progressively reduced while new nuclear power plants of the

PWR-1300 series are commissioned. Afterward the two scenarios are more or less similar as the coal-fired power plants reach the end of their lifetime. The cumulated impact of the coal scenario from 1970 to 2015 can be evaluated to additional emissions of some 2.2 billion metric tons of CO_2, equivalent to eight times the annual emission of CO_2 of France in 1988.

Table III. Environmental Impacts of the Coal Scenario (Emissions in kt/year in 1987).

	CO_2	SO_2	NO_x
Electricity supply (94 TWh)	98,650	17	216
Fossil fuels substituting for electricity	15,700	187	56
Lower GDP	-2,700	-10	-16
TOTAL	111,680	194	256

It should also be mentioned that besides the impact in France, the coal scenario would have induced higher polluting gas emissions in neighbour countries, as the electricity imported from France in the nuclear scenario would have been substituted by fossil fuel generated electricity in most cases. This substitution would have entailed the emission of some 35 million metric tons of CO_2, 130,000 metric tons of SO_2 and 120,000 metric tons of NO_x per annum by the end of the eighties.

3.6. Macroeconomic impacts

The macroeconomic impacts of the coal scenario result mainly from the rise of the electricity price and the lowering of the investments in the electricity sector during the eighties.

The rise of the electricity price induces more inflation. In 1986, the consumption price reached in the coal scenario exceeds the one experienced in the nuclear scenario by 1.2%. The higher inflation rate and the lowering of the purchasing power of wages entail a lower household consumption. The costs of production are higher, leading to a decrease of the competitiveness of French products on the international markets. Moreover, the investments outside the electricity sector, driven by a complex set of factors, including expectations for future demand (accelerator) and relative cost of capital, labor and energy, are lower in the coal scenario than in the nuclear scenario, especially before 1987.

The lowering of the investments in the electricity sector in the coal scenario is responsible for one half of the change in GDP. Until the mid eighties, as the GDP is lower than in the nuclear scenario, the investments are also lower in all sectors of the economic activity. However, after 1985 the investments in the electricity sector increase while the supply system has to be adapted to rising demand.

The impacts of the coal scenario on the main macroeconomic aggregates are summarized in Table IV and Fig. 11. The annual GDP is lower by 0.9% in average between 1980 and 1985 with a peak decrease of 1.3% in 1984. The unemployment is higher until 1995 and the household consumption is lowered by some 0.5 to 1% during the eighties. The slowing down of the household consumption has a short-term negative impact on social welfare but also a more long-term impact on investments in dwellings and other durable goods.

The balance of payments, including the flows of goods and services and the payment of debt interest, is substantially modified by the coal scenario. The imports of fuels, coal or uranium, are different from one scenario to the other. The exports are also different. In the coal scenario, it has been assumed that each one or two years, one additional coal fired power plant of 600 MWe is exported. Nevertheless, the overall French exports are lower in the coal scenario; the electricity exports associated with the nuclear programme are canceled and other exports are reduced by lack of competitiveness of the French industry. On the other hand, the withdrawal of the borrowings needed for the implementation of the nuclear programme leads to a reduction of the interest to be paid.

The overall results are shown on Fig. 12. A small improvement of the balance of payment is observed between 1980 and 1983 but thereafter, until 2015, the need for coal importation and the lack of competitiveness of the French economy entail a larger deficit of the balance of payment than in the nuclear scenario.

Table IV. Macroeconomic Impacts of the Coal Scenario...

%	1976 - 1980	1981 - 1985	1986 - 1990	1991 - 1995	1996 - 2000	2001 - 2005	2006 - 2010	2011 - 2015
GDP	-0.4	-0.9	-0.5	-0.2	0.0	0.0	-0.0	-0.2
Households	-0.2	-0.5	-0.7	-0.5	-0.2	-0.1	-0.1	-0.2
Investment	-1.7	-1.5	1.3	0.8	1.1	0.5	0.2	-0.1
Elec. Investment	-23.8	-18.3	29.1	23.0	11.9	1.8	-4.5	-5.9
Exports	0.2	-0.4	-0.7	-0.3	-0.3	-0.2	-0.1	-0.2
Imports	-0.4	-0.1	0.2	-0.2	-0.1	-0.1	-0.1	-0.2
Unemployment	1.2	1.0	0.6	0.3	-0.1	-0.1	-0.1	-0.1
BP in G.F.	16.3	-21.1	-49.9	-9.6	-34.6	-23.7	-26.7	30.5
BP/(Imp + Exp)/2 in %	0.7	-0.5	-0.8	-0.1	-0.2	-0.1	-0.1	0.1
Consumer Price.	-0.1	0.5	0.7	0.5	0.2	0.1	0.2	0.4
Purching Power of Households	-0.0	-0.3	-0.6	-0.5	-0.3	-0.2	-0.2	-0.4

Source: BP Balance of Payments

4. CONCLUDING REMARKS

The use of a macroeconomic energetic environmental model such as MELODY allows to incorporate in the same framework the technological aspects of an energy policy, its consequences at the macroeconomic level, mainly in term of costs, its influence on the energy markets and on the whole economy and its environmental impacts.

This integrated approach has two main advantages as compared to the traditional supply side approach and more generally to the technico-economic energy models without price effects. First, it allows a quantitative assessment of the macroeconomic and environmental impacts of alternative energy policies; moreover, the structural changes of the economy induced by various energy policies are described by the model and their first order consequences assessed. For example, the coal scenario presented in this study induces a large decrease of the electricity demand, due to lower economic growth and higher price of electricity; this in turn lead to the need for less generating capacity to be installed, 15 MWe instead of 28 MWe.

The French nuclear programme was launched in the early seventies to enhance energy independence and protect the French economy from the impacts of possible fossil fuel price increases. At that time, the protection of the environment was not of prime concern. However the impact of the nuclear scenario on the quality of air is very large; by the end of the eighties, the CO_2 emissions would have been 40% higher in the coal scenario than in the nuclear scenario, the SO_2 emissions 13% higher and the NO_x emissions 15% higher. These results illustrate the rôle of the energy policies regarding environmental protection and show that the environmental impacts of energy policies may be larger than their economic impacts.

The nuclear programme is efficient to avoid fluctuations of the cost of electricity according to fossil fuel market prices. However the nuclear scenario is more capital intensive, mainly because in the coal scenario the electricity demand is lower and thus the required generating capacity is reduced by some 50%. Nevertheless, the large increase in capital cost associated with the nuclear scenario does not override the macroeconomic benefits in term of GDP growth and equilibrium of the balance of payments. During the eighties, the coal scenario entails a lower GDP, due to the higher price of electricity, and a larger deficit of the balance of payments, due to larger fossil fuel imports and lower exports by lack of competitiveness of the French industry.

From the assessment carried out through the MELODY model, it can be concluded that the French energy strategy, based upon a large nuclear deployment, resulted in better economic performances of the country as well as in improved environmental protection.

Specificities	Long-term energy model taking into account all the links between the energy sector and the whole economy. High disaggregation of the electricity generation sector, especially for the nuclear part.
Modelling background	Econometric and technical approaches.
Field of analysis	French economy.
Periodicity	Annual model.
Running period	1970 - 2015.
Utilization mode	Dynamic.
Sectorial disaggregation	Three productive sectors including a fuel sector and an electricity sector with high disaggregation of the latter for the purpose of measuring macroeconomic impacts of the French nuclear programme.
Economic sectors	Four: producers, households, government and external trade.
Number of equations	200.
Main endogenous var.	GDP, employment, unemployment, inflation, energy balance in physical and monetary units, balance of trade, government budget deficit.
Main exogenous var.	Demography, external prices and demands, economic policy, technical variables.
Applications	Main energetic studies in France, methodology applied in Algeria, Jordan, Morocco and Tunisia with the support of the World Bank and UNDP.

Fig. 1a Main features of MELODY-FRANCE.

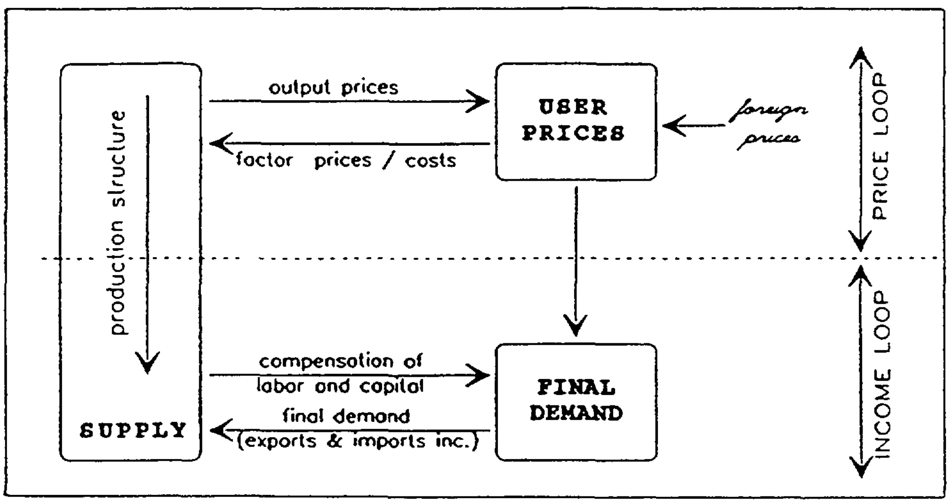

Fig. 1b The MELODY model.

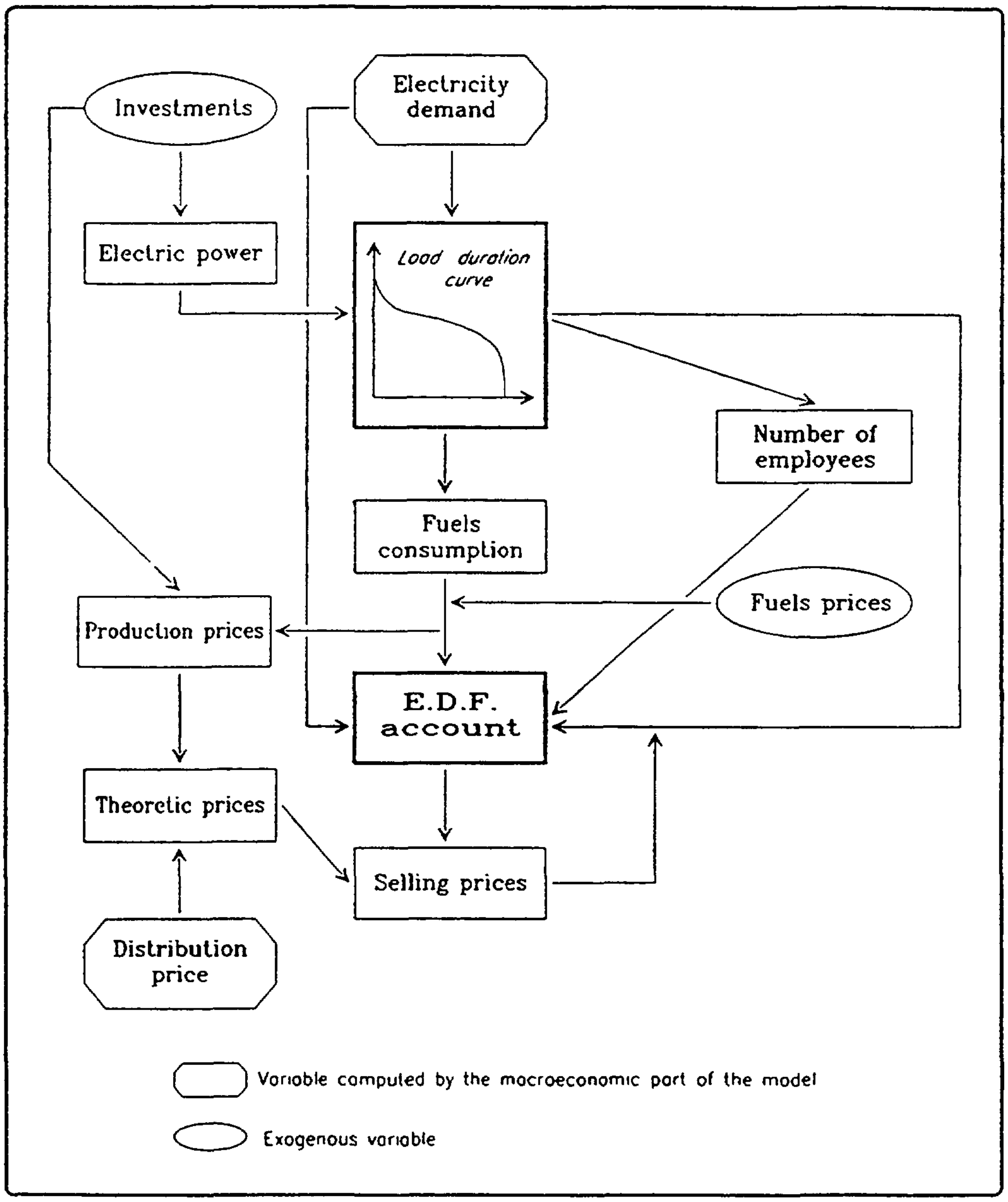

Fig. 2 Electricity production and electricity prices.

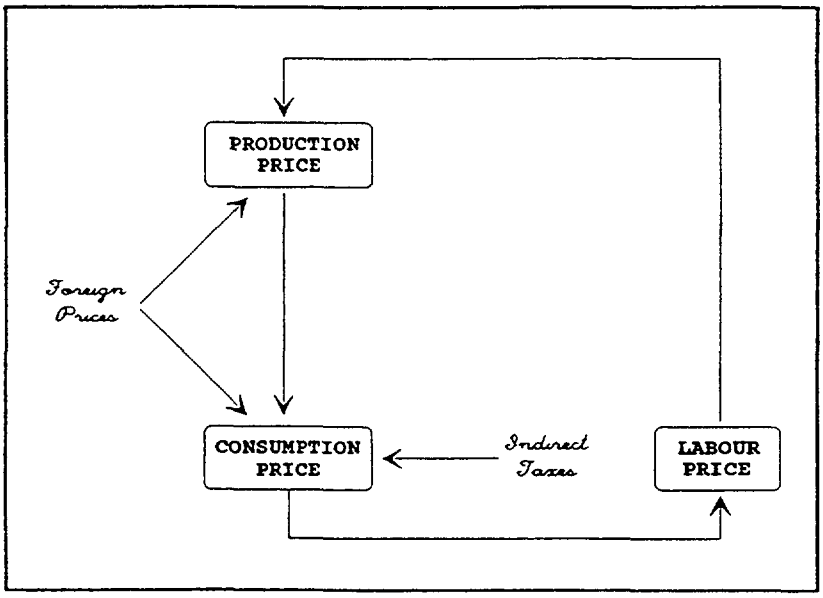

Fig. 3 The price loop.

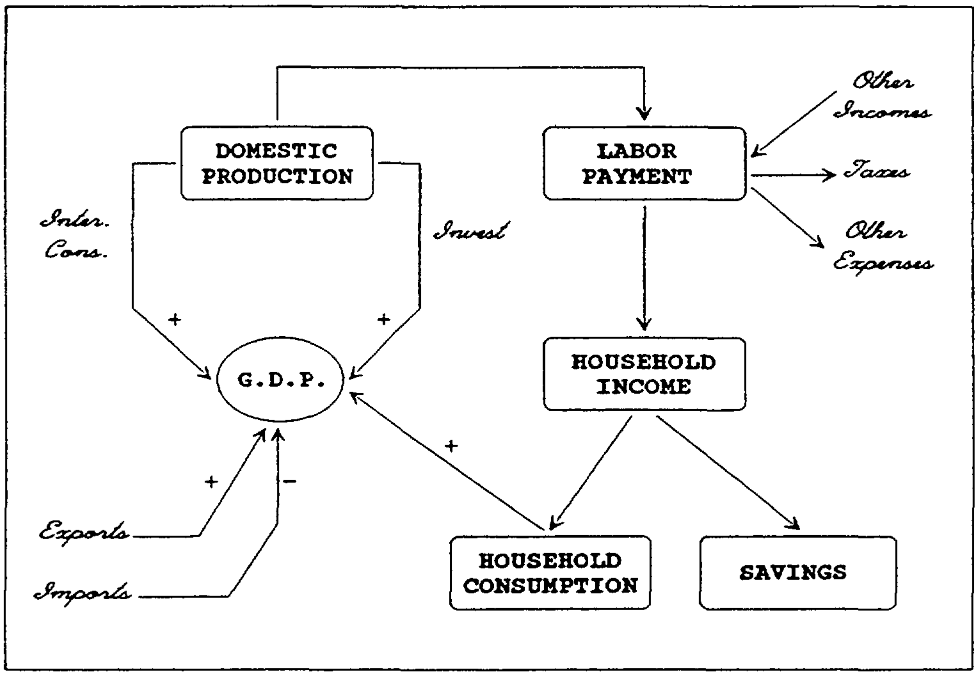

Fig. 4 The income loop.

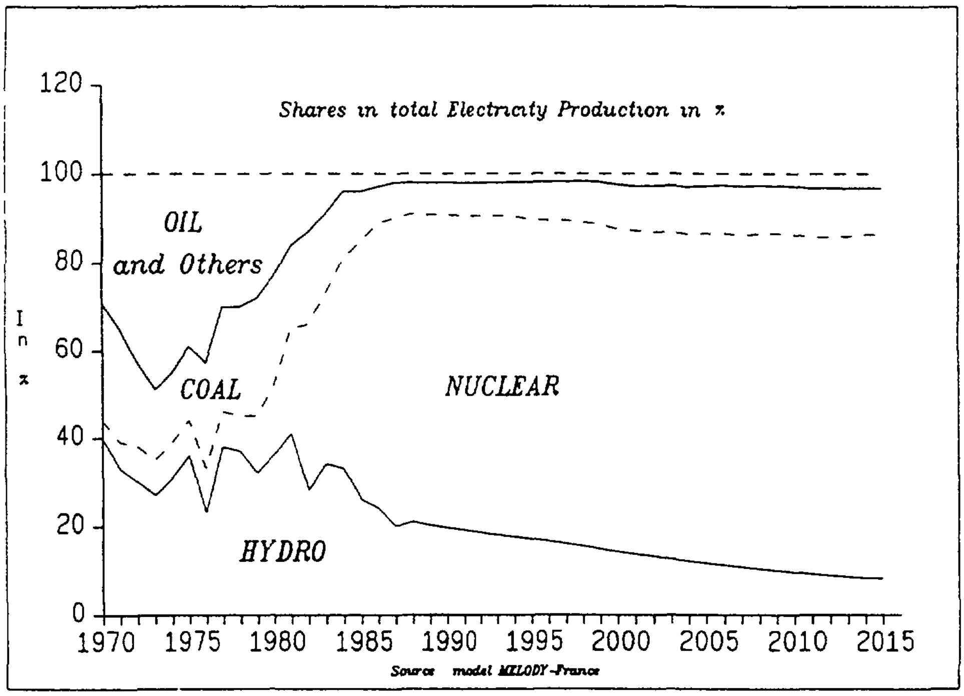

Fig. 5 Structure of electricity production (Reference case).

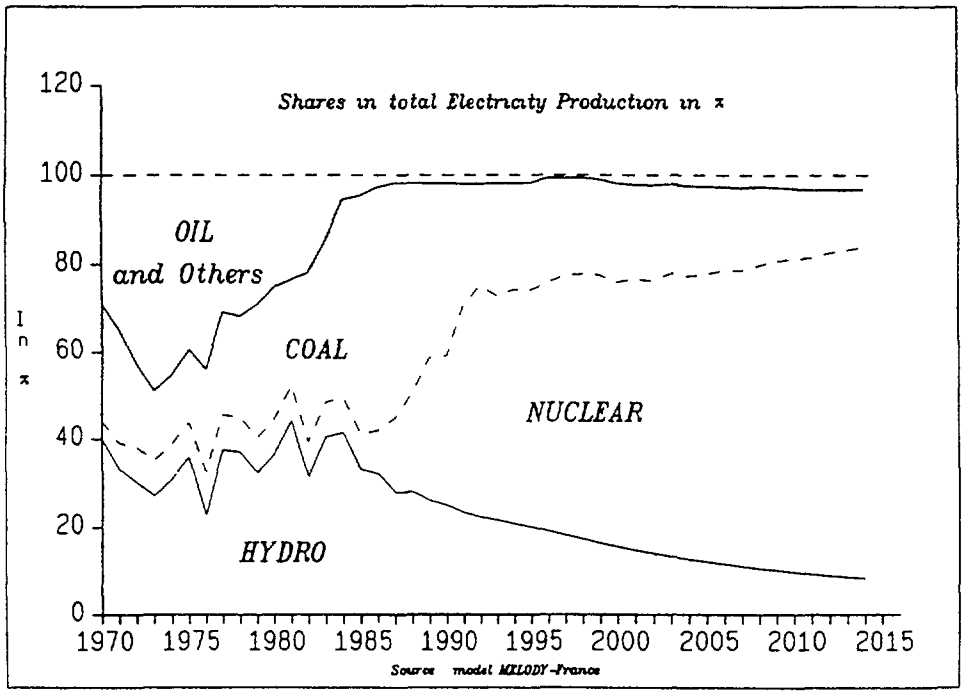

Fig. 6 Structure of electricity production (Coal scenario).

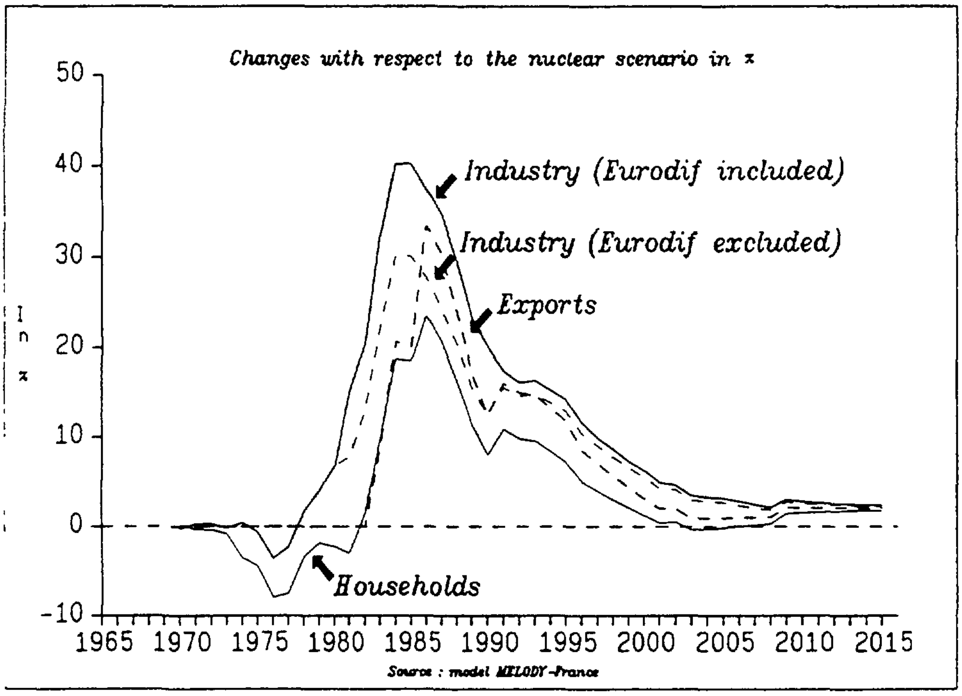

Fig. 7 Electricity prices.

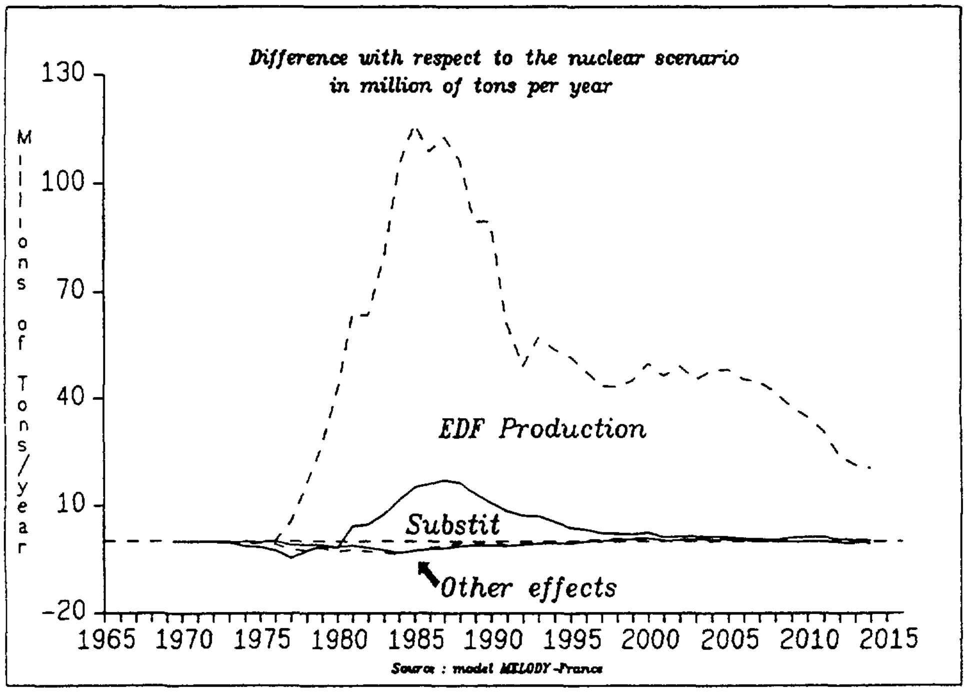

Fig. 8 CO_2 emissions.

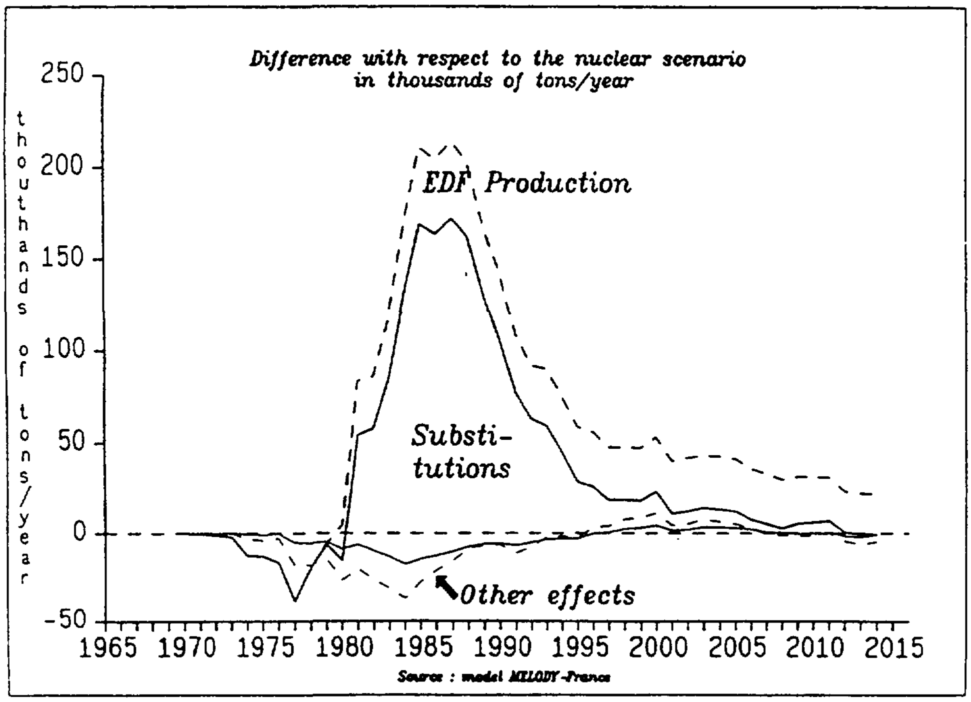

Fig. 9 SO_2 emissions.

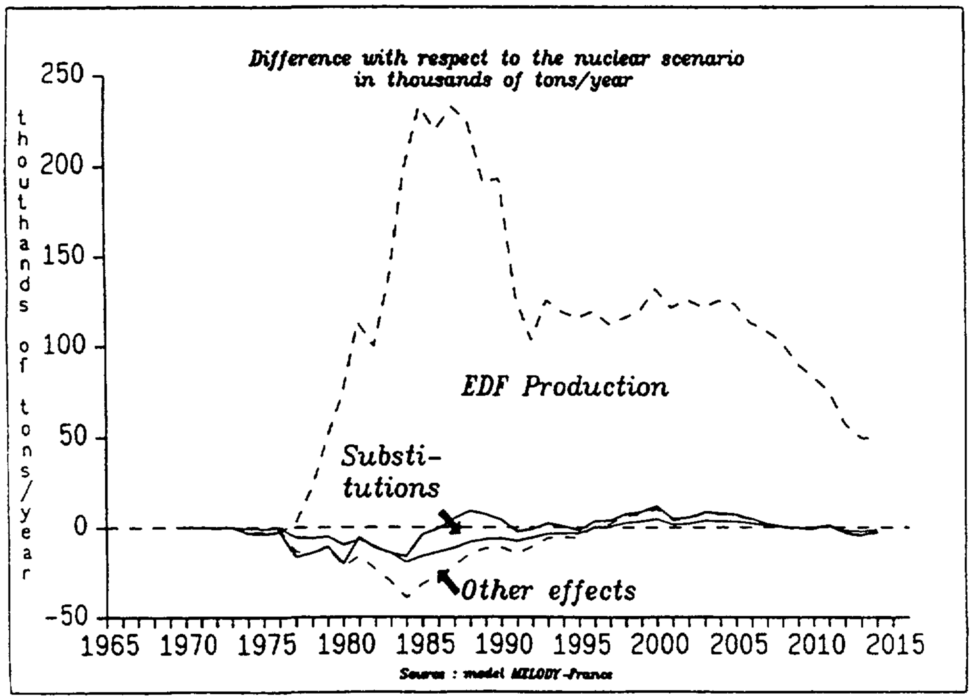

Fig. 10 NO_x emissions.

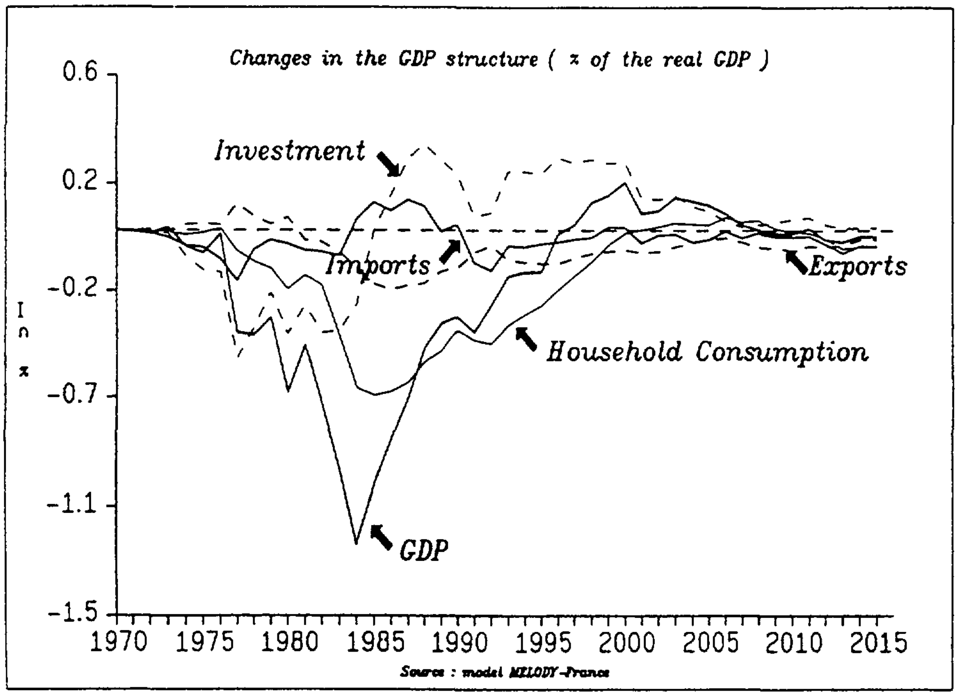

Fig. 11 Main economic aggregates.

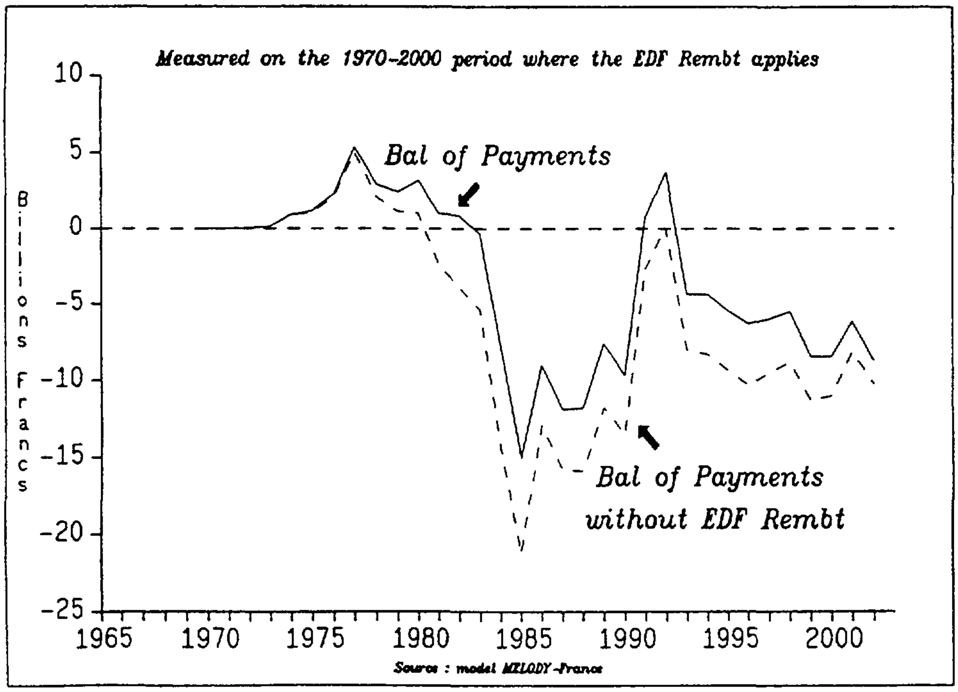

Fig. 12 Impact on the balance of payments.

POWER INDUSTRY IN CHINA: INSTITUTIONAL CHANGES AND ENVIRONMENTAL PROTECTION

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ABSTRACT: The paper reviews the structural change that occurred in the power sector of the P.R. of China during the last years and describes the present situation. It then addresses the question of environmental protection management in the Chinese context. The legal and administrative measures are being implemented to protect the environment, however, it is obvious that the situation is far from being sustainable. The outlook for the coming decade is reviewed and the key issues, from the Chinese point of view, are underlined.

1. GENERAL PLANNING PROCESS IN THE P.R. CHINA

China used to be a country of strict central planning economy. Central government controlled not only the production of almost all the major products, but also the consumption of them. Energy industry was one of those sectors controlled very strictly by central plans.

A plan for production includes two aspects: first, the development plan, and second the annual production plan of the planned period. The development plan includes a set of activities, such as: demand forecast and total scale of development needed, spatial allocation of capital investments, total investment requirement, time scheduling of the investment, technology choice and related policy, and so on. The implementation measures include mainly the control of resources allocation. Capital investments, materials including most of means of production, access to transportation capacity for capturing these means, and labor, were allocated by plans.

Meanwhile, prices, tax rates and tax types, terms of loaning and credit, were used as measures for implementing the plan. In that circumstance, all the enterprises owned by government, and to some extent even the industrial ministries, are order takers. Development plan was decided fully by the central government.

Since open policy and economic reform adopted by China ten years ago, some important changes have taken place,that are described below.

1.1 Authority decentralization

The central government has given part of its authority of economic decision making to provincial and local government. To some extent, some authority have been given to enterprises. Now the share of investments controlled by the central government is less than half of the total. Provincial and local governments, and enterprises share most of the rest; private capital investment, mainly by farmers, accounts to 20% of the total, a lot of which are housing.

The production from enterprises that are not owned by government increased significantly. Production value of industry from collective and private enterprises accounted to 43% of the total in 1988. In general, production of collective and private enterprises is outside plan, although these enterprises are influenced more or less by the economic plan of government.

1.2 Introduction of market mechanisms

Market plays an increasing role in the economy. Now the commodities controlled by plan are less than 50% of the total, and even for the commodities controlled by plan, market influences a lot. The demand side is much more difficult to be controlled by plan than before. Market demand, other than quota allocation, has a more and more oriented supply side. Two important elements cause the market to be stronger: one is the rapid development of non-government owned enterprises, and second the decentralization of authorities.

As the provincial and local governments, as well as enterprises, handle more capital investment, and they cannot make decision based on the overall material balance within their small territories, the profitability becomes crucial criteria for their decision making. Generally, lower level decision makers take into account only the interest of their own units, while at the higher level more attention is paid to the relations between different units and sectors.

The industrial, and other, ministries have their own interests and financial problems, by which their decisions are constrained, especially for that ministries which contracted economic and finance responsibility with the State Council. At this point, industrial ministries become the representatives of the enterprises they owned rather than government representatives.

1.3 Evolution of the price system

A price reform took place but is not complete yet. Before the economic reform, most of the commodities, or say almost all the means of production were priced by government. As government took away all the profits from enterprises and allocated capital and physical products, price was only an accounting symbol. Now in the mixed economy composed by market side and planned side, price has to play the orientation role in the market, and to play the value equilibrium role between market and products in the planned side.

Because the government owned enterprises have their own interests now and face a strong market, they have to care very much for the prices either of their products or of the resources allocated to them. Pressed by the possible inflation, that in fact did happened, the Central Government intended to keep the price of in-plan products more or less unchanged, and adjust some prices if necessary. By now, the price system is rather complex, with two, eg. market and planned, or even several prices for one kind of product, depending on the circumstances of the transaction and the actors on the market.

1.4 Evolution of the investment

Decentralization and market penetration is different by sectors. In general, government owned enterprises contribute more to heavy industries, mainly producing means of production, and less to light industries producing consuming goods. Within the heavy industries, some sectors are controlled by a plan more strictly than others. The electricity sector is still strictly controlled by the Central Government, although some changes did happened compared to the past.

2. ADMINISTRATIVE CHANGE IN THE ELECTRIC POWER INDUSTRY

2.1 The status before 1988

Before 1988, the former Ministry of Water Resources and Electric Power (MWREP) representing the Central Government, was in charge of the power industry as a whole. More than 95% of the power plants and all the grids were directly owned by MWREP. Only very few power plants belonged to some large enterprises generating power for their own use. MWREP divided the electric grid of China into seven district grids, and a few independent provincial grids which had no connection with the district grids. Each district covered several provinces.

For each district, an electric grid administrative bureau representing the MWREP administrated all the power plants and distribution grids in the district. Under the district bureau, there was a provincial electric power bureau in each province, which administrated the power plants and electric grids in the province. At that time, the provincial bureaus had not their own independent accounts of finance. Profits and deficits were accounted at the district bureaus, and they reported to MWREP.

As all the power plants were constructed by government, once a plant was commissioned, the responsibility of the plant was only to produce electricity as designed; expansion and upgrading was not their business. However, according to the technical assessments, proposals of upgrading of some equipments could be raised to provincial bureaus from plants. Provincial bureaus had some money for maintenance and could allocate them to small upgrading projects.

Provincial bureaus were led by province government as well. Provincial bureaus worked with provincial government to produce electricity forecasts for the provinces, and provided their proposal asking for expansion to district bureaus or directly to MWREP. Because electricity had been in shortage for a long time, each province asked for building more electric power plants in their territories. In general, district bureaus would positively agreed with the proposals from the provinces and transfer them to MWREP to ask for more investment to be allocated to their districts.

MWREP was not a banker. As the price of electricity was controlled by government and was low, ratio of gross profit to capital occupation was only less than 14% in 1988. More than 90% of gross profit of electric power industry were taxed by central government. Electricity industry had no capacity of development by self funding at all. What MWREP could do was to ask for more investment to be allocated to electricity sector by the State Council. Apparently, the accumulation of all the investment requirements from districts and provinces was much more than what the central government could afford for the electricity sector, as so many other sectors raised their requirements for investments.

State Planning Commission (SPC) plaid very important role in the budget allocation of Central Government. As the investment requirements from ministries usually were much bigger than the available budget, a lot of trade-off should be taken between sectors. Great efforts were made to keep the balance between sectors, and to ensure that the large projects presented by various sectors fitted in a coherent framework. SPC discussed and negotiated with each sector including MWREP. SPC would not only discuss and negotiate the total budget for power development, but also the specific projects of power plant construction one by one. At the same time SPC would discuss with other ministries to ensure the supply of major raw materials, such as steel, cement, and so on, supply of equipments as generators, boilers and turbines. SPC had also to ensure the supply of coal to power plants, which means that additional coal production should be available on time, and related railway or shipway as well.

In the process of decision making for the electricity system development, MWREP took the role of providing proposals for new projects, conducted technical and economic feasibility analysis, that was constrained by the mechanism of investment system. Once the project was approved, MWREP would operate the project. SPC plaid the role of checking and screening proposals and of the coordinating the various sectors.

However, the top decision maker was not SPC. Overall allocation of resources, including budget, between sectors was decided in the State Council, sometimes directly by the Central Politburo of the Party. Important policy decisions, such as if more nuclear power plants will be built in China, or if export of oil will be stopped or decreased, were also taken by the State Council and if some projects were large enough, involving billions of investment, they were generally dealt with by the State Council.

2.2 Present status

Two years ago, former MWREP was rescinded. At the same time, former Ministry of Coal Industry, Ministry of Oil and Natural Gas Industry, Ministry of Nuclear Industry were rescinded as well. Some national corporations were established based on former ministries, as enterprises rather than governmental agencies. However, as they are national corporations owned by government and are derived from former ministries, some functions of previous governmental ministries remained. For the energy industry, a new Ministry of Energy (MOE) was set up to replace those former energy related ministries. Many officials of the new Ministry of Energy came from the former MWREP. In principle, MOE should take all the governmental functions in the energy sector. But to some extent, the national corporations derived from former ministries, try to keep their autonomy and take their own decisions.

The situation of the electricity industry is complex as no national corporation was set up in that sector. However, the China Electricity Council, as a united organization of nationwide power enterprises and institutional organisms of the power sector, assists the MOE for trading questions. It thus becomes a bridging link between the government and the enterprises. All the former provincial electric power bureaus, either independent or belonging to district bureaus, have or will soon become provincial electric power companies, as enterprises with independent accounting systems. Former district bureaus have transformed, or will soon be transformed, to some Consolidated Power Companies which will be in charge of unified dispatching of the entire networks.

The Ministry of Water Resources (MWR) was set up. Some hydro power station now belong to MWR because the dams and reservoirs are managed by MWR for multi-purpose utilization.

The national company of nuclear industry is responsible of all the development of nuclear power projects.

2.3 The obstacle to change

The above changes aimed at setting apart the electricity enterprises from government functions, and at promoting provincial and local governments responsibility for power development in their territories. To meet such goals some obstacles have still to be removed.

The electricity pricing has to be modified. As the electricity price is too low and controlled strictly by the government, the power industry faces deficit. The government had to admit that some new power plants sell their electricity at a price higher than the one determined by the plan to allow the payback of the investment. This was needed because, provided by government almost freely, electricity industry become an unprofitable sector, fundings from sources other than government budget will be very difficult to find.

The power industry is a capital intensive sector. In order to obtain a better energy efficiency, new designed and constructed power plants are larger and larger. As there is no proper capital market, other than governmental allocation, it is far from easy to collect the funding needed to construct a new power plant, even for provincial governments, not to mention public or private enterprises.

While power plants, especially thermal ones, need stable fuel supply in large volume, primary energy supply and transport capacity availability is out of control from provincial governments.

As a result of the above constraints, the mechanism for power industry development has remained almost unchanged. Investment plan is mostly controlled by central government, although provincial or local governments contribute a little bit more than before.

3. DEVELOPMENT PLANNING IN THE POWER INDUSTRY

In recent years, the government has given priority to power industry, because the lack of enough generating capacity became a bottleneck of the economic development. All the related officials and experts forecasted that the demand of electricity in 2000 will be around 1,200 TWh, that needs at least generating capacity of 240,000 MW_e. It is estimated that about 80% of electricity will be generated by coal. From 1980 to 1988, electricity generation grew at a rate of 7% per year; to meet the 2000 target, a capacity of 12 GW_e will have to be put into operation annually in the next ten years. It was planned that from 1980 to 2000, total energy consumption elasticity would keep on 0.5, but the electricity consumption elasticity would be 1.

If the self-reliance policy of energy supply will not be changed dramatically, coal is and will be the only choice of primary energy for thermal power generation. China is well endowed with coal reserves. Proved coal reserves are over 700 billion tons. While the proved natural gas and oil reserves are very limited. The production of liquid and gaseous fuel are not enough to feed the vehicles, chemical industry and urban households. Since 1980, policy of "substituting coal for oil" has been adopted by government. No oil power plant has been built during the last ten years and there is no plan to build one at least in the next ten years.

Hydro power will be promoted in the future, although the water resources are mostly located far from the consumption centers and relocation of population in the reservoir areas becomes more and more difficult. Huge capital cost for dam and long lead time are additional shortcomings. It was estimated that in the best case hydro power will contribute for 20% to the total electricity generated in 2000, that is to say will keep its present share of the supply.

Nuclear power is still an undefined element in the energy policy making.

Large size and high parameter thermal power generator will be adopted, increasing the efficiency of energy transform. At present, thermal power plants in China have capacities of 100 MW_e, 200 MW_e and for a few of them 300 MW_e. It was planned, that by 2000, 600 MW_e units will become main force for new built plants. No more small size unit will be built in the future, excepting some for co-generation.

It is obvious that global warming issues has not been taken into account along until now in the decision making process for power development.

4. ENVIRONMENT AND DEVELOPMENT IN P.R. OF CHINA

4.1 Framework of the environmental protection management

Before 1980, few officials or experts thought about environment protection issues as a basic policy, although research and practical actions on management and disposal of hazardous residues or emissions had been undertaken for a long period. At that time, people cared about the disposal of hazardous waste, liquids, gases and solids, from industry. Step by step, experts and officials understood that the environment protection should be considered as a much broader system related with economic development and social targets. An Environment Protection Office (EPO) was set up under the State Council as the first national environment protection organization. Then, the National Environment Protection Bureau (NEPB) took the place of the EPO. Later on, NEPB became one part of the former Ministry of Urban and Rural Construction and Environment Protection (MURCEP). Now, the National Environment Protection Agency (NEPA), independent from MURCEP, is responsible of the environment protection policy making and management in China. NEPA has the position of a semi-ministry level in the hierarchical system of central government, but NEPA reports directly to State Council.

There are provincial environment bureaus in each province, which are responsible of provincial environment issues. These bureaus report to provincial governments and directly to NEPA. In cities and counties, there are bureaus or offices of environment protection. They report to the local governments and environment protection bureaus of the higher level.

In every industrial Ministries, a department or special office is in charge of the environment protection issues of the sectors, especially of the enterprises owned by the central government. In MOE, Department of Safety and Environment Protection is the responsible institution in the sector. In local governmental industrial bureaus there are divisions or offices of environment protection. In all the enterprises, there are offices of environment protection, or a staff would be appointed as responsible of environment protection for small scale enterprises.

Governmental environment protection bureaus or offices are authorized to supervise and monitor the implementation of various regulations promulgated. The offices or staffs in enterprises are responsible of helping and advising the managers to ensure that the production activities of the enterprise do not violate the regulations of environment protection.

An "Environment Protection Law" was adopted and promulgated last year by the Standing Committee of the National People's Congress of P.R.China. This law authorized NEPA to supervise and implement the environment protection management of the country. NEPA has been authorized to produce national standards for environment qualities, taking into account the national economic and technical context. Provincial governments are authorized to produce more detailed local standards, eventually more stringent than national ones, if they find it relevant and feasible.

The "Environment Protection Law" has been published for discussion and test for ten years. Many important standards and regulations have been promulgated for some years.

NEPA is lead by State Council. The main emission standards were not issued independently by NEPA, but in cooperation between ministries, especially when they involve huge amount of capital input for disposal equipments or technology substitutions.

4.2 Outlook for the coming decade

China is a developing country with huge population. Natural resources in general are abundant, but the volume divided by population becomes less than the average of the world. Construction of infrastructure is far from completed in any standard. Economic growth rate keeps high, pressured by the employment requirement and the people's expectation of improving standards of life. Enough or better food, acceptable or a little more living space, more clothes and basic movability are still main targets of struggle for most people. The basic targets of environment protection can be nothing but keeping the environment off becoming worse too much.

During the 1980s, the major goal of the national environment protection measures was to strengthen the environment management. A well organized institutional system of environment management has been established in the country. Based on the principle of "dispose the pollutants by the polluters", and adoption of basic standards of emissions, the tendency of rapid deterioration of the quality of the environment has been stopped. But we are still far from a sustainable development framework.

4.2.1 What is the situation of environment quality in China?

Regarding air quality, TSP pollution is still the dominant problem in urban areas. In northern part of China, especially in winter, pollution of TSP from coal burning is very serious. Sediment of ash and suspending particulates are several times over the standard in most cities. In some big cities, vehicle emissions become more and more serious.

Acid rain covers more than 1 million km^2 and in cities of southern China, acid rain becomes worse and worse.

Most of the waste water form industry and households are drained into rivers and lakes, without any treatment. Result of a survey reported among 15 large cities with river passing, 13 of the river sections are severely polluted. Surface water and ground water in many cities are polluted, influencing the drink water.

560 million tons of solid waste are dumped annually almost without any disposal. Accumulated volume of solid waste account to 6.6 billion tons and occupy 536 km^2. It becomes a major secondary pollution source.

Two third of the urban population are living in high noise conditions.

Along with the expansion of industrialization to rural area, the pollution problem has been introduced to some rural areas.

Bio-system faces strong challenge: deforestation has not been stopped. Government strived hard for forestry, but the area covered by forest only accounts for 12% of the total area of China.

Soil and land erosion becomes worse. Erosion goes faster than control. Most serious areas are loess plateau, the upper and middle stream areas of Yellow River, and the upper and middle stream areas of Yanzhi River.

Desert area increases annually; 10.7% of land in North China are desert now; 4 million hectares of farmland, 500 million hectares of grassland and 2000 km of railway are imperilled by deserts.

4.2.2 What is the perspective of economic growth for the next ten years?

Annual growth rate of GNP will remain in the range of 5 to 6% or even higher.

More than 1.4 billion tons of coal will be produced and consumed in China by 2000, 400 million tons more than now and it is estimated that more than 2 billion tons of coal will be needed in 2015.

More than additional 20 million tons of steel will be produced over the present production of 55 million tons.

Population will increase from 1.1 billion at present to 1.25 billion by 2000. More and more population will migrate to urban areas that means consuming more energy and goods and producing more wastes.

5. THE WAY FORWARD

Subject to the above pressures from two sides: environmental and economical, it seems very difficult for us to find out a choice that meets the economic growth and makes the environment conditions more sustainable. Further question could be: do we have alternatives for decreasing CO_2 emission in this case.

The strategy of environment protection declared by the NEPA for the next ten years is composed of two points, one is further strengthen the environment management, another is to promote technology progress.

As to the air pollution control, the first target will remain to control the dust and TSP caused by coal burning. In China, power plants have done more on flue gas disposal than a lot of other industries. Many new ash disposal equipment are under development and will be used once available. Second target could be scrubber of SO_2 as only one sulfur scrubber is used for power plant in China at present, which is perhaps the unique one in China even for all industries, except a few small boilers for experiments. Desulfurization may be considered for some large power plants, especially for specific cities. However, wide spread use of sulfur scrubbers will be difficult to achieve before 2000.

Power industry itself will not be able to consider global warming in the case of China. But anyway, improving efficiency in the energy and electricity sector will be taken into account by State Council, SPC, MOE, and NEPA. Switching from coal to gas or oil will be achieved whenever feasible. The Chinese government attaches much importance to global warming issues and a special office was set up under the State Council to associate the research and exchange information and knowledge with foreign experts and governments. What they want to know before they really take it serious may be:

* Is the global warming proven scientifically?
* What will be the influence of global warming on China and on the world, and when will it occur?
* What will be the feasible approaches and measures to deal with the issues?
* What will be the economic and politic impacts of these measures?
* What kind of international cooperation will be available, especially in terms of technology transfer and financial assistance?

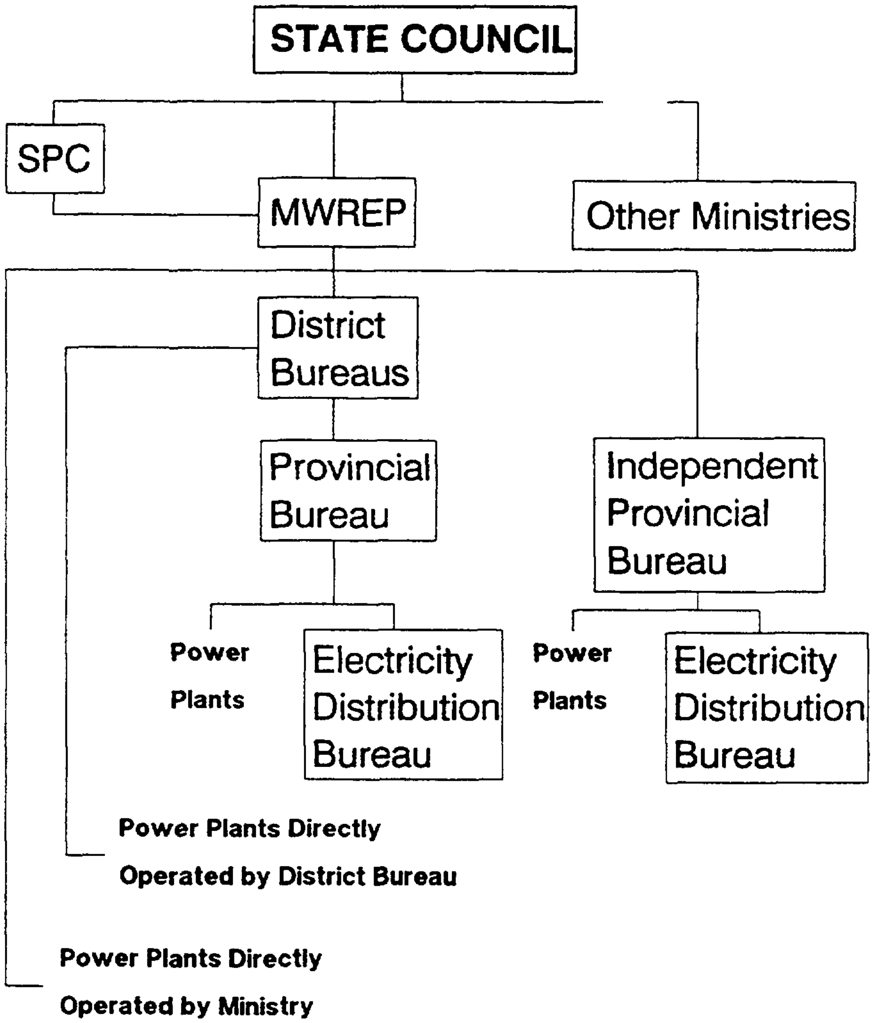

Fig. 1 Decision-Making in the Chinese Power Sector

THE ROLE OF FINANCING INSTITUTIONS

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ABSTRACT: The production, conversion, transport and use of primary energy have considerable impacts on the environment and climate. Throughout the world, the energy sectors face the problem of reducing energy–related emissions, preventing them from occurring and contributing towards the development of environmentally friendly and sustainable energy systems. This requires an integrated planning and decision–making process, in which domestic and international financing institutions also participate since they are frequently involved in the appraisal of electricity projects. To ensure that assessment procedures cover not only project risks and aspects of credit worthiness in a narrower sense but also overall environmental and efficiency aspects, the report outlines elements of a code of conduct. This code of conduct should serve as a guideline for financing institutions involved in financing energy sector investments.

[1] The views and opinions expressed in this paper are strictly those of the author and do not necessarily represent those of the Kreditanstalt für Wiederaufbau. - The author is indebted to Norbert IRSCH for valuable comments and suggestions.

1. SCOPE OF PROBLEMS - AN INTRODUCTION

Worldwide, Economic growth, population growth and increased prosperity in the past have gone hand in hand with a higher consumption of primary energy. Emissions of pollutants harmful to the earth's climate, caused by the use of fossil fuels, have risen largely in parallel. They stem from the production, conversion, transport, and use of primary energy and contribute to the greenhouse effect. Soil and water contamination are adverse impacts as well (for instance, by coal mining, crude oil production and transport, and by reconditioning and refining).

Around the world, the energy sector contributes to the greenhouse effect by about 50%. The damage is caused by carbon dioxide emissions (about 40%) and methane, nitrogen oxides, carbon monoxide and volatile organic compounds without methane (altogether around 10%). The emissions from the burning of fossil fuels do not concentrate only on the centers with the highest primary energy consumption but are spread across the globe ("greenhouse effect") and today endanger all of humanity and the earth's biosphere.

A long–term reduction of harmful emissions that contribute to the greenhouse effect and are linked to the traditional structures of energy supply and consumption can be achieved only through consistent energy conservation, the improvement of energy efficiency, the application of technologies designed to avoid emissions, and through the increased use of non fossil sources of energies (substituting carbon–rich sources of energy).

Such reduction strategies must, however, take into account the energy consumption and supply structures prevailing in industrial and developing countries. With a population share of some 25%, the western and eastern industrial countries today produce about 80% of carbon dioxide emissions, while the developing countries (including the People's Republic of China), with 75% of the earth's inhabitants, account for a mere 20% roughly. Hence the industrial countries are facing the task of substantially reducing their high per–capita emissions. The developing countries, in turn, must make more efficient use of energy with the lowest possible emissions.

International financing institutions, national and international development banks, and commercial banks are frequently involved in the appraisal and assessment of energy and electricity projects. Appraisal and assessment procedures usually cover not only the credit worthiness in a narrow sense; frequently they also take into account the overall cost–benefit analysis, including external effects, social or macroeconomic costs and benefits of power sector investments.

These latter appraisal concepts have so far been applied particularly under financial assistance extended by development banks and international financing institutions. However, there is no commonly agreed set of criteria on which the financing institutions participating in the financing of energy sector investments base the assessment of such projects [1]. The most important prerequisites for establishing such a commonly agreed set of guidelines for energy sector investments are thorough analyses of the overall circumstances in which these investments are carried out.

Sections 2 and 3 of this paper therefore initially examine the key data and overall conditions that determine future investments in the energy sector. These include the structure of energy consumption, the status of the energy sectors in developing countries and industrial countries as well as general characteristics of utility sector investments. Section 4 formulates guidelines for utility sector investments on the basis of the background information provided above. Finally, Section 5 is an attempt to identify alternatives and fields of action for financing institutions in connection with energy sector investments, which then leads to a proposal for a code of conduct.

2. ENERGY CONSUMPTION AND ENERGY–RELATED EMISSIONS IN A REGIONAL PERSPECTIVE

In the introduction it is already pointed out that the emissions caused by the burning of fossil fuels, affecting the earth's climate, are distributed very unevenly worldwide. This is due to regional differences in the structure and level of primary energy consumption but also the extremely differing energy efficiencies.

Considering the determining factors for energy–related emissions by individual regions, the following picture for the country groups listed below results [2]:

Western industrial countries: Low population share (16%), very high production and income level, relatively low energy intensity and relatively high energy efficiency. Energy demand is covered chiefly on the basis of commercial energy sources.

Developing countries: Very high population share (76%), low production and income level, low energy efficiency; use of noncommercial sources of energy (firewood, harvest waste, manure).

Planned economy countries in transition: Lowest population share (8%), production and income level; low energy efficiency; use of mainly commercial sources of energy.

Status–quo prognoses of energy consumption and the development of emissions harmful to the climate forecast a further increase of carbon dioxide from fuel burning (plus 40% up to the year 2005); these prognoses presuppose further economic and demographic growth (with demographic growth tending to be higher in the developing countries), a declining energy intensity in the western industrial countries but increasing energy intensity in the developing countries (in terms of commercial fuels owing to continuing growth in industrial activity, increased urbanization, and further mechanization in agriculture) (Table 1 and [2]).

Table I Key data of determining factors for current CO_2 emissions

	OECD	Developing countries	COMECON
Population share (%)	16.2	76.0	7.8
GDP share (%)	74.3	18.6	7.1
Per capita primary energy consumption (GJ)	199	14	190
Primary energy/GDP (NJ/US$ 1985)	17.5	35.0	30.8

Source: Enquete Commission 1990:459

Investments in environmentally compatible energy production today primarily face the problem of avoiding emissions or reducing them as far as possible, thus contributing towards the development of environmentally friendly and sustainable energy systems. The analysis of the overall circumstances that determine the development of environment–friendly energy systems must, however, also include the structure and status of the utilities and the characteristics of power sector investments.

3. POWER SECTOR STATUS AND CHARACTERISTICS OF POWER SECTOR INVESTMENTS

In many developing countries, investments in the energy sector are considered principally as a prerequisite for further growth and modernization of the national economy. Moreover, electric utilities are a tool for addressing social equity and employment issues and improving the standard of living. Last but not least, this sector is sometimes perceived as a vehicle for raising resources and taxing away surpluses [4].

In many developing countries the desire for growth and modernization and the over–optimism in demand forecasting has resulted in unquestioned funding of power needs, continuous central government subsidies to the sector, nonoptimal or unbalanced investments, and lack of productive efficiency and incentives to maintain technical and financial discipline. Social equity and employment objectives have led to excessive subsidies to consumers, inefficient pricing and consumption, and inadequate resource mobilization [4].

Empirical evidence shows that improvements in access to, and per capita consumption of electricity over the last few decades in many developing countries have required sustained high rates of investment and expansion in total power assets. These investments have been biased mainly towards generation, with consequent underfunding of the distribution facilities [5].

As one consequence of this unbalanced investment, high level of losses are experienced in many countries. High losses drive up supply costs and increase financial burden. In addition, numerous indicators point toward poor quality of service since substandard distribution networks that lead to losses are also responsible for voltage fluctuations and power outages. A deficient energy supply system may cause a high economic cost insofar as consumers are compelled to resort to alternative sources of energy and to simultaneously invest in appropriate facilities. For the utilities themselves this means insufficient internal cash generation and underfunding of all activities, which, in turn, results in poorer service and greater reluctance to raise tariffs [4].

The ex–post evaluations of energy sector investments conducted by the World Bank show that, in power sector investments in developing countries, the main emphasis should initially be placed on improving efficiency and achieving uninterrupted supply, hence the rehabilitation and reinforcement of power systems rather than continued power sector expansion.

In the industrial countries the prerequisites for efficient factor and resource allocation are not completely met either. On the supply side there either is no competition, or this competition is restricted by regional monopolies. Power tariffs are subject to government supervision and influence. They reflect the actual production costs only to a limited extent (externalization of costs) and favor high energy consumption (for instance, by energy–intensive industries) and non electricity–specific applications (such as electricity for heating) through a tariff system with lower unit prices for higher consumption levels. This tariff structure tends to favor the expansion of power supply but not so much the improvement of efficiency in using available energy, thereby causing avoidable costs to the national economy and a continuing rise of environment polluting emissions.

Except for certain countries with specific potentials for the use of renewable sources of energy like hydropower, electricity is produced worldwide almost exclusively on the basis of commercial, nonrenewable energies and almost everywhere in large electric power plants. At first glance, there are many reasons that explain the tendency to build relatively large and centralized power plants: economies of scale in planning and operation, opportunities for improving coordination and efficiency, and reliability gains. On the other hand, large, centralized power plants also require larger and longer–term investments (especially for transmission and distribution), often a fairly large group of shareholders, unless only state or parastatal agencies are involved simply because of the sheer size of the project in order to limit the project and credit risks. This, however, is also linked with higher transaction costs (coordination of donors, delays in allocation of funds, in construction and project implementation). Furthermore, large–scale production and supply facilities not always but often involve bigger environmental problems (land use and siting impacts, severeness of possible environmental accidents), which must be taken into account. These latter arguments show that there is such a thing as diseconomies of scale; today these arguments call more strongly for investments in decentralized energy production and supply facilities to be operated predominantly on the basis of renewable sources of energy.

Such a conclusion also finds support considering the characteristics of the investments made in power plants in the past. Their characteristics [6]:

- **Large amounts of equipment and high capital intensity:**

Grid-based energy supply is one of the most equipment–intensive sectors of a national economy; in the Federal Republic of Germany, the share of assets in plant and equipment of the utilities on average accounts for around half their balance sheet total, while the average share in other industries is merely one fourth.

According to a World Bank study about 58% of investments went into power production in the developing countries between 1965 and 1980, whereas only about 31% went into transmission and distribution. In the Federal Republic on the other hand an average of 43% of investments by the utility sector was spent on power generation, 47% on transmission and distribution.

— **Limited divisibility of power plants:**

The limited divisibility of power plants makes the parallel adjustment of capacities to the respective demand, which is necessary in order to optimize costs, quite difficult. This is particularly true of countries and national economies with a low level of power generation and supply and few centralized generation plants. While consumption is rising or falling relatively continuously, power plant output has so far been increasing in leaps and bounds due to technical aspects. Owing to long planning phases, generating capacities are inelastic, and short–term adjustments are difficult or not possible at all.

— **Long operating life and consequently long investment cycles:**

The planning, construction time and operation of large scale electricity generation plants last several decades, which considerably heightens the risk of the economic usability of the plant. In addition, owing to the lengthy replacement investment cycles, economic energy reduction potentials (e.g. through more rational use of energy or energy substitution) can generally not be realized within a few years but only in the long run.

— **Major dependence on technical developments influences both supply and demand:**

The technical development in the field of power generation takes place in huge steps (historically seen the development in power generation goes from hydro power stations to coal fired stations and then to nuclear power station). In the future a larger share of total energy will be provided by combined cycle power stations (with a total energy efficiency of 40 to 50%), and in particular by renewable energies (e.g. photovoltaic, solar and wind energy). Technical developments on the demand side, however, which are mainly induced by input prices and influence energy needs and the energy efficiency of power driven appliances and plants, are relatively continuous.

— **Major dependence on external factors:**

In principle, investments in power plants (as regards type and scope) are dependent of the availability of the respective source of energy, but nowadays political and ecological aspects are often more decisive for their use rather than economic aspects. Other risks are connected with the time intensive authorization procedure.

Against this background, status and character of investments, some criteria are given in the following section, which might serve as guidelines for utility sector investments but at the same time determine a framework for activities and possibilities to exert influence on the part of the financing institutions.

4. GUIDELINES FOR UTILITY SECTOR INVESTMENTS

From the above it is quite obvious that over the next decades the requirements of environmental and climate protection will play a decisive role in power sector investments. Taking into account different regional priorities these requirements may best be fulfilled by systematically saving energy, by improving energy efficiency, by employing techniques to avoid emissions and by increasing the use of renewable energies.

Reduction strategies require that all stages of the process are equally considered, from primary energy production, to conversion, distribution and consumption and finally to waste disposal. The solutions aimed at must not only be sufficient from a microeconomic point of view but also be optimal for the economy as whole and allow for a sustainable and environmentally friendly energy system.

The broad rational underlying all national level planning and policy–making is the need to ensure the best use of scarce resources, in order to facilitate further socioeconomic development efforts, to improve quality of life, and to protect the environment and to prevent global climate changes. For the power industry this implies a (non exhaustive) list of **guidelines**, which planning institutions and utilities in the developing countries as well as the industrial countries should follow as much as possible when taking investment decisions.

First, power needs to be produced and consumed (more) efficiently. Economic efficiency implies both: a) efficient consumption of power and energy by providing efficient price signals that ensure optimal energy use and resource allocation, and b) efficient production of power and energy, by ensuring the least–cost supply mix through the optimization of investment planning and energy system operation [5].

Second, it has to be recognized that the energy sector is part of the whole economy and energy planning therefore analysis of the links between the energy sector and the rest of the economy is required. When comparing cost and benefits of different power generating alternatives the energy system as a whole (the complete fuel cycle) has to be considered.

Third, at all stages of the power consumption process (generation, conversion, distribution, final consumption), prices should correspond to the long–term macroeconomic marginal costs. Subsidies, for social reasons should not be handed out via lower electricity tariffs but via per capita allowances; otherwise energy–saving attitudes and investments will be discouraged and production processes and industries that tend to be energy intensive will be favored. External effects are to be internalized as much as possible by legal measures (polluter pays principle).

Fourth, at all stages of the energy utilization process, there should be permanent and effective incentives to minimize costs and to conserve energy. The energy markets require workable competition and greater private participation on the supply side. Especially in the power sector with its state, semi–state or regional monopolies, too, all legal possibilities to achieve this goal should be fully exploited.

5. CONSEQUENCES FOR FINANCING INSTITUTIONS

In most countries it is the responsibility of the state to build up legal institutions and to create suitable laws so that the basic principles and possible measures described above become effective. Quite frequently governments, however, are not in the position to efficiently set up such institutions and enforce the laws and legal rules. For this reason there is also a broad field for supporting activities to be assumed by financial institutions to ensure an environmentally friendly approach to energy generation and consumption.

The above description of the conditions under which energy sector investments take place, makes clear that an integrated planning and decision–making process will only be feasible and efficient if all leading financial institutions urge that environmental and efficiency aspects are given due weight when assessing electricity projects. This is of special importance in countries where environmental regulations (emission standards), normally set up and enforced by government authorities, are lacking or not efficiently enforced. Otherwise competition among financial institutions might lead to a situation where those institutes (banks) that attach little or no attention to ecological aspects will be given preference by the investors due to lower total investment costs.

Therefore, national and international financing institutions should commonly agree on a **code of conduct** which serves as a guideline for a systematic analysis of energy projects according to a comprehensive set of criteria. The idea behind the development of this code and behind ensuring the largest possible acceptance of them, is to prevent that, for the sake of short–term advantages, individual financing institutions try to finance projects with actual or potential negative impacts on the environment and/or global climate. The code of conduct would thus ensure that on the financial side, too, macroeconomic and ecological criteria are given due weight within power sector investments.

In the following, a short outline of the possible elements of such an code of conduct, which refers partly to the principles described in section 4 will be presented:

— **Protection of the environment and saving of resources:**

Financing must give preference to energy generation plants that treat the environment carefully and save resources both during construction and later in operation and thus make an environmentally friendly and sustainable energy system possible. The assessment of effects on the environment and resources has to be based on an environmental impact assessment procedure, which describes and assesses as comprehensively as possible the impacts on the environment that might occur. Environmental impact assessment procedures have already become an integral part of project appraisals conducted by development banks and international financing institutions in the context of Financial Cooperation with developing countries.

Before building new electricity generating plants, however, all possibilities should, as a general rule, be fully exploited in order to increase the efficiency of existing plants (e.g. via rehabilitation), to reduce technical and non–technical losses or to combine different uses such as combined heat and power stations.

— **Climate protection:**

Financing must give preference to investments that help avoid and/or reduce emissions of carbon dioxide and other trace gases that influence the global climate.

— **Tariffs:**

Financial institutions should verify and ensure that energy is offered at prices without externalization of costs. Prices should be cost–covering at all stages up to final consumption.

Here the long–run macroeconomic (social) cost should be taken as a basis for calculation as far as possible.

— **Operating agency:**

In the financing a stronger decentralization of power plants and a larger participation of private investors have to be ensured as one means of improving power utility performance and relieving in particular the governments of developing countries of the economic burden of financing chronic deficits of state–owned enterprises.

— **Security:**

A further condition for a participation in the financing of power plants is security with respect to supply, operation, accidents and crises.

— **Political and social impact:**

The project/energy system to be financed must not involve any irreversible constraints and must offer end–users the possibility to participate in the project implementation.

Quite obviously, the effectiveness of such a code depends on the extent to which the energy sectors (utilities) rely on investment loans. In this respect, too, there are significant differences between industrial and developing countries. Due to relatively low own funds of the utilities in developing countries, the financing institutions' possibilities of exercising influence with respect to environmental concerns are much more important. But still, this influence would only have an effect if a code of conduct outlined above, accepted by all leading financing organizations, was established in the first place.

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POLICY INSTRUMENTS: ECONOMIC INSTRUMENTS VERSUS REGULATION

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ABSTRACT: The paper compares the tools available to governments in order to aim at a sustainable development. Two types of measures, direct regulations and economic instruments, may be used in this regard. The advantages and drawbacks of both tools are described. Up to now, the direct measures have been widely preferred for many reasons, especially for preventing direct danger to man and environment. However,the optimum allocation of available resources can only be achieved with economic instruments. A suitable policy, therefore, requires now a combination of direct and economic measures especially in the governments applying free-market mechanisms. The paper concludes that certificates, or tradable permits, are likely to offer the highest degree of efficiency to guarantee an efficient protection of the environment at the lowest global costs for the society.

1. INTRODUCTION

A reliable and a low cost supply of electricity is one of the most important prerequisites for the healthy development of the national economy. Even so the conversion of primary energy to electrical energy, in one way or another, inevitably has significant consequences for the environment. Reducing these consequences to a minimum, or at least keeping them in check, is an ever more pressing necessity. Neglecting the environment in which we live is a shortsighted policy which, for the sake of short-term advantages, consciously or unconsciously, puts up with longer term damage and cost.

In almost all industrial and economical activities based on traditional technology and production processes, the reduction of harmful emissions to the environment is inevitably involved with increased costs. A company that voluntarily introduces pollution restricting measures automatically reduces its competitiveness compared with other companies that do not. It follows therefore that adequate protection of the environment can generally only be achieved when effective, and at the same time just, conditions are laid down governing all those engaged in pollution causing activities.

2. GOVERNMENTAL STRATEGIES

Governments have effectively two types of measures at hand they can implement to create the necessary conditions for keeping pollution in check and providing incentives for its further reduction:

- **Direct** regulations: Regulations laying down - in black and white - the permissible limits for environmental emissions.

- **Economic** measures: Taxes, levies and emission control certificates, whereby pollution of the environment is proportionally linked with punitive costs to the parties responsible.

2.1 Direct regulations

The advantages of **direct regulations** are:

- a concrete limitation on the emission of harmful substances into the environment;

- and, frequently, the achievement of fast results.

Regulatory measures, it follows, are thus perfectly suited to prevent direct dangers for both man and environment.

Direct regulatory measures, however, also have the following disadvantages:

- they provide no incentive for voluntarily reducing pollution below the preset standards;

- they have a static effect - i.e. further adaptation to keep pace with developing knowledge and technology becomes extremely difficult.

2.2 Economic measures

The advantages of **economic measures** may be enumerated as follows:

- The increased costs put on all emissions to the environment, even when these remain within officially permitted limits, provide an economic incentive, assuming measurements to be accurate, for the further reduction of pollution.

- They provide those causing pollution with the freedom of decision to reduce environmental emissions first and foremost at precisely those points where this can be done most efficiently - to put it another way: at those points where the greatest reduction in emissions can be obtained at the same expenditure.

- They have a **dynamic** effect because they go on working, even where results have already been achieved, until the lowest possible emission is reached. This dynamic effect can be intensified by the appropriate application of free-market strategies, e.g. by the levying of increased penalties with time or - in the case of emission control certificates - by reducing the amount of pollution rights as time goes on.

- They stimulate innovation to reduce environmental pollution as efficiently as possible.

2.3 *Offsets in applying the appropriate environmental policy*

In those countries where legislators, governments and authorities have taken, or are taking, initiatives to protect the environment this takes place, **largely** (or even entirely), by **means of direct regulation**: official regulations lay down concrete emission standards for noxious substances - whether gaseous, liquid or solid - from production plants and other industrial installations, from vehicles, and even in some cases from private households. Infringements against these regulations are regarded as infractions of the law or, in serious cases, as punishable offenses.

There are two reasons why, despite the advantages of economic measures mentioned above, up to now almost exclusively the instrument of direct regulation has been used:

1. State authorities are long accustomed to regulating social policy by the application of civil and criminal law.

2. In those cases where there is specific danger to persons or the environment to be prevented or overcome as quickly as possible, the establishment of official standards for environmental pollution is often necessary.

Regulatory means are thus essential, but at the same time not entirely adequate. Provided there is no specific danger at stake and that the action to be taken is of a more preventative nature, the effectiveness of legal measures is frequently low, being at the same time inflexible and economically inefficient.

No economic system is better placed to balance costs and profits and to maintain these in equilibrium as the free market economy. If proof is needed this can be only too clearly seen in the present economic and ecological collapse of the centrally planned economies.

The classical factors of production - land, labor and capital - must today be slightly modified, replacing the term land for the wider concept of the environment as a whole.

Because none of the world's resources exist in unlimited quantities it is right to term them as scarce resources. This applies equally today to the environment in many countries and to an increasing extent on a global scale. The aim of all economic planning must thus be the **optimum allocation of the available resources.** This is done most efficiently of all by the market itself.

Under the conditions so stated, the optimum control of environmental protection is thus provided by a combination of legal and economic measures, the emphasis being as far as possible on the application of free-market strategies.

3. ECONOMIC INSTRUMENTS IN ENVIRONMENTAL POLICIES

The primary economic instruments of government influence are thus taxes, levies and tradeable pollution rights (certificates). Further economic instruments include compensation schemes or the establishment of environmental liability. These function with mostly the same effect as the economic instruments mentioned above, but will not be further explained in the present paper.

While taxes and levies work by influencing the price to be paid for using the environment, tradeable certificates primarily provide a quantitative regulation: by issuing a limited quantity of environment utilization rights the government is in a position to determine the permissible burdens placed on the environment and so to place the parties in possession of those utilization rights in a competitive situation so that the price for using the environment in terms of a resource will be dominated by a free-market mechanism.

3.1 Taxes on environment

Of the economic measures mentioned above, the taxation of environment utilization is the least efficient. One of the main disadvantages is the **overlap of fiscal and control functions.** Taxes by definition have a financing function: they exist to provide the State with the necessary means to fulfil its functions. They are governed, it follows, by principals of social justice and effectiveness.

If taxes are to assume an additional control function, they can no longer fulfil both functions satisfactorily. This can be very clearly illustrated by the example of an environment utilization tax. If this tax is to fulfil its control function, with the result that harmful influences on the environment become less and less, it can no longer do justice to its other task, i.e. of providing finances for state funds. If, on the other hand, it proves a reliable long-term source of income for the State, then it is failed in its function as a control mechanism.

What is more, many taxation specialists warn against overloading an already complicated taxation system with additional political aims, thereby making it even more complex and cumbersome than it is already.

A third argument against the levying of environment taxes – and this applies to virtually the same extent for environment levies – is that it is very **difficult to set the correct** level. If they are set too low, those causing pollution will simply pay their taxes or levies, but do nothing to reduce emissions to the environment, because this would simply entail higher costs. In this event, there is thus no incentive to initiate further improvements in environmental protection. If, on the other hand, the taxation or levies are set too high, they effectively rob the environment user of the financial means he requires to initiate the requisite pollution abatement measures.

At this point I should like to make brief mention of the much discussed plans to improve the environment through the taxation of energy use. A tax on energy in general can certainly stimulate more economic energy use and thus in many - but by no means all - cases have the effect of reducing pollution to the environment. If, however, the primary aim is environmental protection, energy taxes show themselves to be a poor control instrument, as they do not provide a systematic orientation in the direction of low-polluting primary energy sources or energy conversion processes .

3.2 Environmental levies

Environment levies, as opposed to environment taxes, are far better suited to the improvement of environmental protection in accordance with specific requirements, because money from **levies, by definition, is purpose-specific**. This means, in the first place, that the finances derived from said levies can themselves be utilized to the benefit of the environment, e.g. by providing finance for research and development, or for investment in specific pollution abatement measures. In the second place, the setting of levies as well as the provision of detailed structure for the levying system (e.g. Boni, Mali) can be adapted much more flexibly and effectively to the aim in question than is the case with environment taxes for the reasons discussed above.

Even so, the problem remains with environment levies of determining their absolute level in such a way that the required aims are reached in practice and that they are not — as discussed above — either ineffective or counterproductive. Nobody, whether in the State or private sector, can succeed in setting and structuring levies so precisely as to fulfil the aim of environmental protection with the highest possible efficiency. (In other words: in such a way that the available financial resources are always utilized precisely where they reduce environmental pollution to the highest extent and most rapidly.)

3.3 Certificates (tradeable permits)

This high degree of efficiency can best be achieved by means of tradeable quantitative environment utilization rights (certificates). The effective free trade, within certain limits, in such certificates means that within these limits which can be determined locally, regionally, supra-regionally or even globally depending upon the pollutants in question, a market for said utilization rights is established, in which prices are determined by the laws of supply and demand.

Here, there is no problem in determining the price for the utilization of the environment. It is determined in conjunction with the marginal profit for individual interested parties when they either buy certificates, because this is cheaper than investing more money in expensive pollution abatement measures, or sell certificates because they are in the fortunate position of being able to reduce environmental emissions at lesser cost than they would need to pay for a certificate.

In this way it can be guaranteed that — depending upon the current technological state of the art — the most effective protection of the environment is achieved with a specific quantity of money. An additional incentive of the system is that, contrary to taxes and levies, it functions without excessive administration costs. It even has the further advantage of providing a precise control mechanism for the pollution of the environment as a whole in terms of spatial and temporal threshold values that are not to be exceeded. After all, it is the number of pollution rights issued that determines the extent of pollution at a particular period of time and in a particular region.

The system of tradeable pollution permits is an efficient instrument to realize the more general concept of compensation. Compensation, however, faces two major problems:

- the proper definition of the geographical area in which compensation is acceptable or meaningful;

- in the case of transboundary or even global compensation areas, the possibly considerable differences in industrialization and economic power of the various countries competing for pollution rights.

Concerning the proper definition of the geographical area, it is evident that for different polluting substances emitted by plants, different sizes of the area are to be considered. Looking, for instance, at solid particle (dust) emission, it is clearly not helpful for the neighbors of a plant, if that plant continues with a rather high emission while the compensatory reduction of particle emission is done at a plant several hundred kilometers distant. - But if we look at CO_2, which does no direct harm to men, nature and the lower atmosphere but enhances the global greenhouse effect in the stratosphere, it would be meaningful and physically acceptable to allow for global compensation. Reducing CO_2 emission by 1 ton in China has the same effect on the greenhouse problem than doing it in Europe or elsewhere.

Thus, in the case of CO_2, defining the relevant area for compensation represents no problem at all with a view to the material impact of these emissions. In the case of other polluting substances, however, the problem of properly defining the relevant area must be addressed carefully and mainly be based on the known facts about propagation of the polluting substance in question taking into account the meteorological situation. Solutions have already been found in some cases where the so-called "bubble model" has been applied.

Concerning the second problem mentioned above, namely the huge differences in economic power between various countries, it is evident that an emitter in a developing country normally cannot afford to buy pollution rights (tradeable permits) at the same price than an emitter in a highly industrialized country.

This problem, however, is not specific to the proposed system of tradeable pollution permits but is the more general problem of international burden sharing where global measures are needed. A solution has to be looked for in the frame of the Global Environment Facility (GEF) applying the principles of Affordability and Fairness.

A mechanism for such a solution could be an international fund in the framework of assistance to developing countries. The task of the international fund would be to give subsidies to developing countries either for buying pollution permits or for investing in pollution reduction, depending on which alternative is economically more favorable in each individual case. Such a procedure would be consistent with the aim of optimal allocation of funds.

Coming now back to the general features of the instrument of tradeable pollution permits, one further conceptual aspect requires mention: namely the **temporarily limited validity** of the pollution rights or, in modified form, the sliding depreciation of said permits. In this way, in addition to the existing incentive of reduced costs, there is a further stimulation of progress towards the reduction of environmental pollution.

If one wishes to achieve such a dynamic system within the context of a regulatory framework, this can essentially only be achieved by lowering the standards generally in large steps - or, more generally, by placing higher demands corresponding to the technological state of the art. That way, however, rules out the consideration of individual factors and influences and the possibilities existing within specific installations with the consequence that the same pollution abatement measures must be introduced on an overall basis thereby incurring widely differing specific costs and ignoring specific optimum solutions. A procedure of this type reduces the incentive for companies to invest in improved technology of their own accord and, therefore, on the most efficient basis.

Economic measures on the other hand, if properly applied, give companies freedom of decision and action. Effective appeal is made to their innovative imagination, thus resulting in much more efficient achievements of the aim of providing environmental protection as quickly and as far reaching as possible.

4. CONCLUSION

In the process of implementing sustainable energy and electricity policies, government may use a set of direct regulations and economic measures. Although each of them has certain advantages and drawbacks on the other hand, tradable pollution permits (negotiable quantitative environment utilization rights), seem to offer a relatively promising and one of the most efficient ways, in a free market economy, to ensure environmental protection and economic development.

PROCESS AND STRUCTURE OF PLANNING AND DECISION MAKING IN A SMALL COUNTRY (FINLAND)

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ABSTRACT: The paper describes the main features of the Finish energy policy. The licensing procedure for power plants is described and the case of nuclear power plants is addressed in detail. A decision-making process is presented considering public participation, addressing environmental impact assessment of each stage of the process.

1. INTRODUCTION

General aspects and questions involved in national energy policy planning and decision-making of any country are i.a. as follows:

- Guidelines for energy policy and decision-making on the basis of the requirements of the Sustainable Development.
- Introduction of environmental and health requirements in the national energy policy and decision-making in general.
- Integration of the international agreements and recommendations into the national policy and decisions.
- Combination of Government control, policy-making, enterprise initiatives and market forces in order to reach sound decisions.
- National energy policy in a legislative form if possible.
- Introduction of fiscal and tariff instruments being the right methods to conduct policy and individual decisions and the danger of their counter effect on economy in the long-run.
- Reaching the balance between different energy options in the decision-making procedures.
- Implementation of the Environmental Impact Assessment.
- Guarantee of democracy and public participation, however, without paralyzing decision-making.
- Role of media in decision-making.

Some of these points are considered, from the view of a small industrialized western country such as Finland, in the following presentation.

2. ENERGY SUPPLY IN FINLAND

Finland covers an area of 338,000 km^2, which makes the country one of the largest in Europe. It has a population of 5 million and an average population density of 14 per square kilometer.

The high proportion of energy intensive processing industries and the high requirements for space heating make the total energy consumption per capita in Finland one of the highest in the OECD area. The absence of high grade fossil resources has made Finland rather heavily dependent on imported energy, mainly oil and coal but also on natural gas, electricity and nuclear fuel.

In 1990, the primary energy consumption in Finland was the equivalent of 30 million tons oil (Mtoe), i.e. more than 6 tons of oil per capita. The main domestic energy sources in Finland are hydro power, wood, wood waste, pulping liquors and peat. About 30% of the energy demand is covered by indigenous fuels and hydro power. Crude oil and oil products constitute the major part of imported energy. In 1990 oil supplied about 30% and natural gas about 7% of the total energy need.

The Finnish energy supply system is in many respects one of the most expedient in the world. In combined heat and power generation (CHP) the Finns are world pioneers.

Nuclear power is produced in four units: two 445 MW_e PWR units in Loviisa and two 710 MW_e BWR units in Olkiluoto. All these nuclear power units are working very well. The share of nuclear energy in 1990 was 15% of the total energy, and 30% of electricity supply.

3. FINLAND'S GENERAL ENERGY POLICY PLANNING

In Finland the planning of the energy policy is outlined in **Programs on Energy Policy.** These are periodical programs given by the Government. Giving such programs is a praxis and not provided by law. The present Program on Energy Policy dates from the year 1983, but some parts of it are not up-to-date. At present, the next program, **"Outlines of the National Energy Strategies"** is under preparation in the Ministry of Trade and Industry and is expected to be completed in 1991 - early 1992.

The Energy Policy Programs define the goals and objectives of the national energy policy. Traditionally these programs have taken into account the economic growth, security of supply and efficiency. In the Outlines of the National Energy Strategy new emphasis will be given to the environmental and health aspects of the energy supply.

In the preparatory process of an Energy Policy Program, the **Ministry of Trade and Industry (Ministry responsible for energy affairs)**, in cooperation with the parliamentary **Council of Energy Policy (Advisory Body of the Ministry of Trade and Industry)**, outlines a draft of the program. Based on this draft a special **Government Report on Energy Policy Measures** is prepared for Parliament handling. The Members of Parliament and political parties give their opinions on the declaration during a parliamentary debate. The results of the parliamentary debate must, thereupon, be taken into account by the Government in the decision on the Energy Political Program. In other words, the Energy Policy Program is completed by the Government after hearing the Parliament. There is no defined validity period for this type of program, but normally it would be valid until the presentation of the next program.

It is traditional in Finland that the political parties forming the Government agree upon a special **Government Program.** This political agreement defines the conditions and guidelines the government parties concerned will follow during their term. The Government program may also include important energy political decisions. For example, the Government in 1987-1991 declared in its program a nuclear moratorium for the term of its mandate. Thus, the Government programs may in fact have a significant impact on the energy policy.

Important bodies for the preparation of the Finnish energy policy are also parliamentary and governmental committees. The most important parliamentary committee is the **Council of Energy Policy.** The Governmental Committees may be permanent, such as the **Advisory Committee on Nuclear Energy Clarifications**, or topical ad-hoc committees. Examples of the recent topical committees are the high level **Energy Committee**, which studied the energy options for Finland and the **Finnish Commission for Environment and Development** for the follow-up work of the World Commission on Environment and Development (Brundtland Report).

As a general remark, one should acknowledge that Finnish energy policy planning addresses environmental and health aspects as more and more important elements in the decision-making process. One example is that an environmental impact assessment for all energy, installations is becoming the general requirement for all policy documents and legislation.

4. LICENSING OF MAJOR POWER PLANTS

The general law governing the licensing of power plants and electrical installations is the **Law on Electricity Supply Systems**. One of the leading principles of this law, after its latest revision of 1989, is that the planning of the future electricity supply is based on initiatives of the electricity producers (utilities, municipal electricity undertakings, etc.). The Law on Electricity Supply Systems covers the licensing of the major power plants using fossil fuels (250 MW_e or more), whereas licensing of nuclear power plants, hydro power plants and import of electrical energy are subject to special legislation. The construction permit for a major fossil fuel power plant is granted by the Government. The condition for granting the permit is that construction of the power plant is necessary for the national electricity supply and considered adequate in the framework of the energy plan of the country. The construction permit will contain conditions to ensure safety and to avoid pollution.

It must be recognized that at present the few requirements set on licensing of the fossil-fuel power plants are not in balance with the very strict requirements set on nuclear power plants in the **Law on Nuclear Energy**. However, a revision of the Law on Electricity Supply Systems is in progress which will introduce the requirement for an environmental impact assessment to apply to fossil fuel power plants as well.

4.1 Licensing of nuclear power plants

The present Law on Nuclear Energy in Finland came into force in 1988.

In the new law the first step in the licensing procedure is the **"Decision in Principle"** by the Government. In this decision a nuclear power plant project will be considered at a very preliminary stage from a general point of view. The central aspect is the benefit and interest to the society as a whole.

The following permits and licenses are issued after a positive **"Decision in Principle"** by the Government:

- construction permit,
- import and export permits for nuclear materials (fuel permits),
- operation license.

The Government will grant the construction permit and the operating license. The fuel permits will be granted by the Ministry of Trade and Industry and in some cases by STUK (Center for Radiation and Nuclear Safety). The fuel permits cover both the import of nuclear fuel or nuclear materials needed for the fuel, and the export of the spent fuel.

<u>4.1.1 "Decision in Principle" by the Government</u>

Since wider democracy was required for the new nuclear law, the central question was whether the **"Decision in Principle (Political Decision)"** on a new nuclear power plant should be made by the Parliament, or the Government, or by referendum.

The Law on Nuclear Energy adopted a procedure whereby the first step in licensing would be a Decision in Principle by the Government. This decision, if positive, would then be subject to the final ratification of the Parliament. This means that Finland has adopted a system where democracy by representation in the parliament will be applied in the basic licensing of a nuclear power plant project. Thus, a clearly administrative decision is addressed to the law making body because aspects connected with public participation motivated such a system.

4.1.2 Application

The application for the Decision in Principle shall be submitted to the Government. It shall present the preliminary plans and information on e.g. the following:

- Specifications on the activity and project (in this case a power plant),
- Necessity of the plant from the point of view of the energy supply of the country,
- Intended site(s),
- Purpose, size and intended operation time of the plant,
- Outlines of the technical properties of the project,
- Safety criteria to be applied to the construction and operation,
- Competence and available resources of the applicant,
- Financial status of the applicant,
- Financing of the project,
- Ownership of the intended plant site and situation of the land use planning on the site and in the surroundings of the site,
- Population and other activities of the society in the surroundings of the site,
- General assessment of the environmental impact of the project and criteria for limiting the environmental effects,
- Outlines of the fuel supply,
- Outlines of the nuclear waste management.

The authorities handling the application may also require additional information.

The need for extensive information serves two purposes. On the first hand, the applicant must have considered the project in all aspects before making the application. On the other hand, the Government should be provided with necessary information so as to enable it to make a comprehensive risk-benefit analysis concerning the project.

4.1.3 Consideration by the Government

The first requirement for a new nuclear power plant project is that it must be in the **interest of the society as a whole**. When considering this requirement the Government shall apply discretionary consideration in its risk-benefit analysis. (This free discretion is in contrast with the bound consideration where the permit shall be granted, if the requirements set by the law, are fulfilled).

The central elements considered by the Government to assess that the project is in the interest of the society as a whole are:

- The necessity of the power plant from the point of view of the energy supply of the country,
- The suitability of the intended site and the estimated environmental impact of the project,
- The adequacy of the fresh nuclear fuel supply and the nuclear waste management.

4.1.4 Statements

The Government also needs several statements from different bodies, governmental and others for its consideration. The most important are:

- A positive statement of the municipal council on the intended site is an absolute prerequisite for a positive "**Decision in Principle**". Thus, the municipal council has the binding right of veto in the issue. The right of veto of the municipal council reflects the principle of self-government of the Finnish municipalities. The consequence is that if the statement of the council of the municipality concerned is negative, the Government is not allowed to make a positive "**Decision in Principle**" concerning the said site.
- The statement of the control authority, the Finnish Center for Radiation and Nuclear Safety (STUK), also binds the Government if the statement is negative. STUK will in its preliminary safety assessment, forming basic parts of its statement, evaluate whether it is possible to implement the project so that the safety requirements can be fulfilled. The ALARA-principle given by the ICRP (As Low As Reasonably Achievable) will be applied in the assessment.
- The other statements are requested from:
    - Ministry of Environment,
    - Ministry of Interior,
    - Ministry of Defence,
    - Ministry of Finance,
    - Neighboring municipalities,
    - Water Administration,
    - County Administrative Board,
    - Regional Council of Land Use Planning,
    - Council of Energy Policy,
    - Nuclear Energy Commission,
    - Bank of Finland,
    - and other relevant bodies.

4.1.5 Local hearing

During the handling of the "**Decision in Principle**", the Ministry of Trade and Industry shall provide the local inhabitants and authorities with a possibility to present their opinion regarding the application, in writing. This will be organized through a public announcement defining the procedure. In addition, the Ministry shall arrange a **public hearing** in the community where the nuclear power plant is intended where oral and written opinions about the project can be presented.

The opinions shall be brought to the attention of the Government for its discretion in the deliberation on the "**Decision in Principle**".

In order to facilitate the organization of these local hearings, the applicant of the "**Decision in Principle**" shall prepare a public pamphlet, which presents in general terms the nuclear power plant project. The pamphlet is subject to the approval of the Ministry of Trade and Industry. A description of the project on the basis of the application shall be presented in the pamphlet. It shall also include an evaluation of the environmental effects and the safety of the project. After approval by the Ministry of Trade and Industry, this declaration shall be made generally available to the public.

Certain aspects ought to be noted in the local hearing system:

- it is not possible to set any limitations on the right of participation in a local hearing;
- the individual opinions presented locally do not bind the Government. They form material for discretionary consideration by the Government;
- presenting an opinion in connection with the local hearing does not constitute the right to appeal;
- although the new law does not mention the sequence of the local events, it would be logical that the local hearing is carried out before the municipal council will give its statement on the project to the Government. The local hearing does not bind the municipal council, but it can, of course, take it into account before giving its statement.

4.1.6 Parliament ratification

A positive "**Decision in Principle**" by the Government, that implementation of a nuclear power plant project is in the interest of society as a whole, must be addressed without delay to the Parliament for ratification. The Parliament either approves or abrogates the "**Decision in Principle**". The Parliament does not have the right to change the contents or wording of the Decision. This means that the Decision is handled in a simplified procedure and not in the form of a law. Prevention of the Parliament to change the Decision of the Government is justified, because essential parts of the Government's Decision are safety related conditions, which the Government has agreed upon with the controlling safety authority. These conditions cannot be matters of taste or political will, because for the most part they stem from the law, safety requirements, and international requirements and recommendations. This aspect reflects a special difficulty which arises when the Parliament, as a legislative body, will be involved in making an administrative decision, which according to the Finnish system normally should fall within the competence of the Government.

4.1.7 Prohibition to proceed

Before the Parliament has ratified the "**Decision in Principle**", the applicant shall not be permitted to engage in measures, which could make it difficult for the Government and the Parliament to decide the matter according to their free discretion. This means that no construction work is allowed, nor is the applicant allowed to make binding agreements with any nuclear power plant supplier, before the "**Decision in Principle**" is ratified by the Parliament.

4.1.8 Procedure after Positive Decision in Principle

Following a positive "**Decision in Principle**", ratified by the Parliament, the next step by the applicant will be the selection of the plant supplier and submitting the application for a construction permit to the Government. Then the construction permit, fuel permits and operating license follow in sequence. These permits and licenses specify in detail the implementation of the environmental impact assessment and ALARA-principle, as well as define the safety and health requirements.

5. OTHER LEGISLATION APPLICABLE TO POWER PLANTS

Several laws in the general legislation also cover electrical power plants. For example:

- The Law on Construction and Land Use Planning, requires a land use plan (site permit) for a power plant. The land use plan includes i.e. an evaluation of the environmental and health impact of the project from other points of view than nuclear and radiation.

- The Law on Water Resources requires special permits of water courts for the use of cooling water in the power plants.

- The Law on Air Protection includes the Government decision on limits for air emissions. On the basis of this law, a new coal-fired power plant, using fossil fuels must be equipped with up-to date technology for SO_2 and NO_x removal. Under this law e.g. the following international air protection agreements and recommendations will be introduced into the Finnish system:

    - General Agreement, Geneva 1979,
    - Helsinki Declaration 1985 (SO_2),
    - Sofia Declaration 1988 (NO_x),
    - Toronto Climate Conference 1988 (SO_2).

- The Law on Public Health

6. CONCLUSION

Making the decision on major power plants in Finland is based on:

- National Energy Policy Programs,
- Government Programs,
- Initiatives of the electricity suppliers.
- Positive "**Decision in Principle**" of the Government on a nuclear power plant, this decision being the guideline for other power plant decisions.

Making the decision on nuclear power plants in comparison with that of fossil-fuel power plants is still imbalanced in Finland.

The Environmental Impact Assessment requirement is going to be applicable in all power plant investments. Consequently, all permits and licenses will include detailed environmental conditions.

PUBLIC INFORMATION AND PARTICIPATION

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ABSTRACT: The development of power generation systems, like any other technological choice, will need policies broadly supported by public opinion. Involving the public in decision-making will be possible and efficient, provided a successful communication process will develop between technical experts, responsible authorities, and every group of concerned persons. The communication should address all the topics including the risks of accidents and the complexity of policy aspects of the problems, the challenge being to deliver messages understandable by the layman. The credibility of the information are of utmost importance and will be enhanced by the agreed consensus among experts at the international level.

1. INTRODUCTION

Environmental and health impacts connected to the production of electricity have become increasingly apparent to the public. The demand for electricity is expected to increase and new generation facilities have to be built. Public opposition have made it increasingly difficult to build additional generation capacity even in response to obvious needs. The outcome of a process of planning additional capacity has become very uncertain making the industry hesitant to approach controversial solutions. The complexity of the issues makes it difficult to give an objective truth and the views of experts are varying in wide ranges. The emerging debate on future electricity generating systems is expected to be difficult. The options available are all expected to contain major components of disagreement. The seriousness of the concerns may demand even costly alternatives to be considered, which implies that a high level of consensus has to be reached before decisions can be made. The global dimension of the problems adds another component of tension, where solutions have to be coordinated through international negotiations and agreements. Public involvement in decision making processes have, however, been already considered in [1].

2. UNDERSTANDING THE CONCERNS OF THE PUBLIC

Unwanted effects such as accidents and environmental pollution has shown that technological progress contains mixed blessings. Big industry has in the eyes of the public been insensitive to their concerns and been looking only for its own profits. The concerns on nuclear power are connected to a lack of credibility of technical performance, but also of societal institutions, which partly are due to inadequate communication processes. Natural risks have been compared with risks of energy production, but the comparisons have been seen as attempts to promote nuclear power. Research in risk perception have shown that the concept of risk contains far more facets than the simple mathematical definition of risk as the product of probability and costs of consequences [2],[3]. Psychological and cultural factors together with the character of the risks will influence how people react to them. Friends and peers are actually more important for how people view risks than argumentation by experts. An understanding of people, their beliefs and wishes has to be built into the communication process to make it successful.

3. REASONS FOR INVOLVING THE PUBLIC

The main reason for involving the public in the energy debate is connected to the principles of decision making in a democratic society. Citizens have the right to be informed about plans affecting them and also to influence the plans. Correct responses in the society relies on communicated and understood information. From a pragmatic point of view there are certain dangers in not involving the public. Actors excluded from the decision making may plant the seeds of an opposition, which even may reopen and undo earlier decisions. The operation of dangerous installations such as nuclear power plants relies on mediated responses in emergencies, which means that emergency plans have to be communicated. A process of communication initiated early enough has also the benefit of identifying areas, where in depth analyses are necessary.

4. WAYS OF INVOLVING THE PUBLIC

The most natural way of involving the public is through normal processes of political decision making. This means that the issues are debated in media, opinion polls are arranged and decisions are subjected to a vote for majority. It can be tempting to prepare technical issues within a small elite of specialists forgetting the social and political dimensions. Controversial issues have always to be prepared by soliciting broad political support. In order to have a true public involvement it is necessary that the process is started before the final decisions are made. A planning of the communication and public involvement is important for structuring the process. The public involvement can be seen as a process of incremental decision making aiming at building a consensus. Agreed plans for the involvement should be followed with a reasonable accuracy in order to avoid incidental happenings, which are interfering with the planning process. The actual involvement of the public will vary during different phases of the planning process. Used instruments for communication and involvement will also depend on the target groups of the public.

5. ACTORS IN THE PROCESS

Selected policies for the generation of electricity in the future will influence the whole society, which implies the involvement of politicians, the industry, governmental agencies, public interest groups, local residents, media representatives, etc. Specialists connected to the groups of actors will prepare background material for the argumentation. The actors differs with respect to resources and power, but this should not be allowed to influence the recognition of justified claims from anyone.

6. OPENNESS AND CONTENT OF THE COMMUNICATION

An institutional response to a problem brought into the open is often a denial of its existence. Communication has to be as truthful as possible in order to be efficient. An open communication to the public is the only working solution in the long run, but it can be difficult to institute. Information has sometimes to be kept confidential, but it is then necessary to communicate the reasons for the confidentiality. All aspects of proposed solutions including benefits and risks have to be communicated at the same time without a bias. Values, preferences and priorities of the interest groups involved should be expressed as accurately as possible. Concerns of the stakeholders should be given proper consideration. Communication has to be targeted to specific receivers in order to make messages understandable. In the communication on complex issues it is easy to make slightly untruthful simplifications, but such should always be avoided. In handling misconceptions it is necessary to remember that they might be based on strong beliefs making them almost impossible to correct. A communication based on an attitude, that it is necessary to educate the public is not likely to provide the required constructive approach to the debates. The difficulty of finding a proper mode of communication is aggravated by the necessity to take cultural values and norms into account.

7. QUESTIONS TO BE ANSWERED IN A DEBATE ON ELECTRICITY GENERATION

The emerging debate on policies for future electricity system development is one example, where many different issues have to be communicated. In this debate the experts should be able to give understandable answers to questions like:

- is additional generating capacity really needed, or is it possible to manage with electricity conservation?
- which primary energy source is the most suitable and why is it not always possible to use renewable energy sources?
- what are the targets and what is a reasonable level for the efforts of environmental protection?
- how serious is the concern for the greenhouse effect and what kind of abatement measures are possible?
- are nuclear power plants safe and what are the effects of low dose radiation?

It is evident that there are no simple answers to the questions, but that message has then to be communicated. It should also be made more transparent to the public why and where experts are disagreeing.

8. CREDIBILITY OF THE COMMUNICATION

Credibility of the involved persons and institutions is crucial for a successful communication. Credibility can only be built over time by a truthful and open communication on any issue of concern. A continued demonstration of high professional skills is another important part in acquiring credibility. A communication process is actually an exchange of both explicit and tacit messages. The credibility assigned to a specific message is depending on its source and the consistency of the message with messages from other sources. The weight a messages is assigned is depending on the social position of its source in the society. Important messages should therefore be given by high level decision makers and they should be consistent with other messages on the same issue. Consistency implies also that there is an agreement between messages transmitted and decisions made.

9. EXPECTED OUTCOMES OF INVOLVING THE PUBLIC

The outcome of a process of public involvement will by definition be uncertain. It is necessary to accept that the process can cause considerable delays. Building a sufficient consensus, it should be possible to proceed with the policies and thereby to avoid the societal costs of undecideness. Disagreements can be expected to remain, but collecting the support from a fair majority of the stakeholders involved should make it possible to proceed. The necessary consensus is not likely to be reached without a considerable amount of compromises and bargaining between the stakeholders.

10. COMMUNICATING AN UNDERSTANDING OF COMPLEXITY

The difficulty of communicating an understanding of the components of an integrated policy making framework to the public is the complexity of the systems. Mathematical models used for the prediction of consequences of decisions can often be understood only by experts. The models are sensitive to underlying assumptions and the results are difficult to interpret. Laymen have also an understandable distrust in the use of computers for the calculation of costs and benefits of complicated scenarios. It is still necessary to use quantitative methods for the comparison of decision alternatives, but the argumentation has to be made transparent enough before communicated. This requirement can be met only by a skilful popularization using simplified models of the systems. Experts should also be able to give a clear answer to what suggested policies really mean for the involved.

11. EMERGENCY RESPONSE PLANNING

The possibility of major accidents has to be admitted, because that is the only truthful message. A denial can also lead to deficient planning of emergency responses [4]. Deficiencies in emergency responses demonstrated in recent accidents have had an actual contribution to the lack of credibility of institutions involved. Emergency responses has to be planned for all potentially dangerous installations, because only then correct mitigating responses to an accident can be ensured. The problem is however to communicate the dual message of adequate safety and the need for emergency planning. The emergency planning should also include the procedures for the communication during and after the emergency. The societal responses of taking care of and compensating possible victims of an accident are another part of the emergency planning.

12. CONSUMER PARTICIPATION

Consumer participation is expected to be required for some of the action to decrease environmental and health impacts of industrial production. A transfer to energy efficient products, increased recycling of waste, and environmentally benign materials will depend on the multiple choices of very large groups of consumers. Policy instruments have to be developed to steer consumer choices toward more optimal modes of electricity use. These choices are, however, not made only depending on cost and benefit considerations, but also on other factors such as consumption habits, environmental consciousness, cultural background, etc. Public information on energy conservation and environmentally benign products can be expected to play an important role in actually reaching the targets set in the beginning of the planning process.

13. CONCLUSIONS

The successful implementation of policies aiming at a sustainable electricity system development will rely critically upon public participation, acceptance and support. This can only be achieved by consistent and credible information of the public of the risks and credits of the alternative strategies, using well-established and reliable communication channels.

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