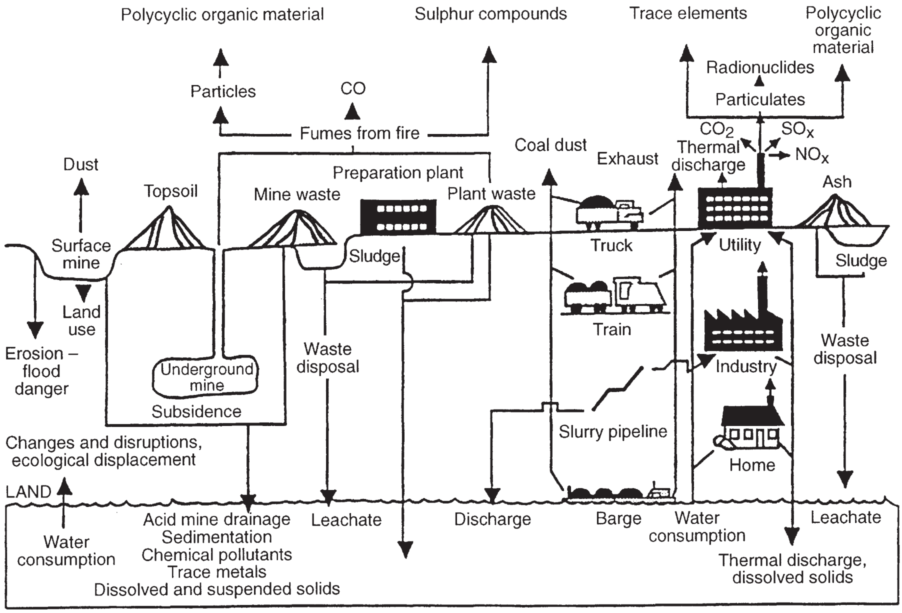

TECHNICAL REPORTS SERIES No. **394**

Health and Environmental Impacts of Electricity Generation Systems: Procedures for Comparative Assessment

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1999

HEALTH AND ENVIRONMENTAL IMPACTS OF ELECTRICITY GENERATION SYSTEMS: PROCEDURES FOR COMPARATIVE ASSESSMENT

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Printed by the IAEA in Austria
December 1999
STI/DOC/010/394

TECHNICAL REPORTS SERIES No. 394

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VIC Library Cataloguing in Publication Data

Health and environmental impacts of electricity generation systems : procedures for comparative assessment. — Vienna : International Atomic Energy Agency, 1999.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914) ; no. 394
STI/DOC/010/394
ISBN 92–0–102999–3
Includes bibliographical references.

1. Electric power systems—Health aspects. 2. Electric power systems—Environmental aspects. I. International Atomic Energy Agency. II. Series: Technical reports series (International Atomic Energy Agency); 394.

VICL 99–00233

FOREWORD

Comparative information on health and environmental impacts of various energy systems can assist in the evaluation of energy options. Over the last twenty years several studies have attempted to quantify such impacts for a wide range of energy sources. Many of these studies have taken the proper, fuel cycle approach, where impacts from fuel acquisition through to waste disposal are estimated. During the last few years several major studies have been completed and new studies have begun. The results can provide useful insights and help to promote further studies of impacts for many more technologies, sites and regions. However, this is not always straightforward as different studies have used different methodologies and assumptions particular to their needs.

When the IAEA started the co-ordinated research programme (CRP) on Comparative Health and Environmental Risks of Nuclear and Other Energy Systems (1994–1998) to promote case studies in different countries, it was recognized that there was a demand for guidance in addressing the difficult issues that analysts must resolve in setting the scope and boundaries of a study, choosing the general methods to be used, and deciding how best to quantify and present the results. To meet this demand, the IAEA started the development of the present report to aid in the design and implementation of comparative risk assessment studies, by setting out a generally acceptable framework for carrying out such assessments and identifying the major technical issues and uncertainties in the assessment process.

Issues to be discussed in the report were established initially, and a working paper was drafted in 1995. The principal contributors to the working paper were D.J. Ball (United Kingdom), K.S. Dinnie (Canada) and M. Dreicer (United States of America). The working paper was reviewed by experts at a Research Co-ordination Meeting of the CRP in November 1995, and a detailed outline of suitable guidelines was developed at the meeting. The guidance was drafted in 1996 by R. Lee (USA), S. Hirschberg (Switzerland), C. Boone (Canada) and R. Dutkiewicz (South Africa), and subsequently reviewed at a Technical Committee Meeting in May 1996. The report was finalized by R. Lee, S. Hirschberg and R. Wilson (USA), together with Y. Matsuki of the IAEA, incorporating comments from members of the Technical Committee and from participants of the previous Research Co-ordination Meeting.

The IAEA wishes to express its gratitude to all those experts who contributed to the development and completion of this report.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The use of non-sustainable energy resources and systems will continue to increase in the future to support the world's growing population. It is necessary to use these resources in a way that is efficient, that reduces their impacts on human health and the environment, and that reflects societies' other priorities.

The availability of sufficient supplies of affordable energy is a prerequisite for economic development, and development is necessary for achieving the standard of living to which most peoples in the world aspire. However, growth and development must be sustainable. A generally accepted definition of sustainable development is "development which meets the needs of present generations without compromising the ability of future generations to meet their own needs" [1]. Sustainable energy development applies the principles of sustainable development to the energy sector. A fundamental tenet of sustainable energy development is the efficient use of energy, human, financial and natural resources. Most countries of the world have endorsed the concept of sustainable development. The challenge is to undertake assessments and comparisons of energy options from the perspective of sustainable development.

In practical terms, sustainable energy development means that human health and environmental impacts, resource depletion and intergenerational equity implications should be considered along with traditional economic and technical issues in the planning and use of energy options. Economic development and environmental protection objectives should not be considered mutually exclusive but should be pursued as common and strongly linked goals. Global concern over the level of environmental degradation has increased and society expects that economic development should not be pursued at the expense of degradation of the Earth's natural resources.

The production and consumption of electricity lead to environmental impacts which must be considered in making decisions on the way in which to develop energy systems and energy policy. The key to moving towards sustainable energy development lies in finding the 'balance' between the environmental, economic and social goals of society and integrating them at the earliest stages of project planning, programme development and policy making.

The environmental consequences of energy production and use must be known in order to manage and choose energy products and services while keeping in mind the needs of future generations. The requirements for information in support of corporate and/or government planning and decision making are changing, there being a clear emergence of concerns for environmental stewardship and accountability. Thus, there is a need to integrate environment more effectively into all aspects of energy planning and decision making in order to make current decisions environmentally prudent, economically efficient and socially equitable, both now and for the future.

Environmental degradation is a global problem, but it must be dealt with on several different scales: local, regional, national and international. For example, a number of countries have agreed to participate in stabilizing CO_2 emissions at 1990 levels by the year 2000 under the United Nations Framework Convention on Climate Change. This commitment could have implications for the way in which electricity is produced in different countries. In order to determine how best to meet future energy requirements, the environmental implications of various alternatives should be considered.

All forms of electricity generation, and indeed all parts of the fuel chain[1], have impacts, both positive and negative. Comparative assessment can be used to assess and compare impacts of existing and potential fuel chain facilities. The results of comparative assessment can also play a role in developing overall energy policy for a country or a region. Societies must assess these impacts to determine which electricity producing options involve the greatest net benefit to the current generation without placing undue burdens on future generations or compromising their ability to meet their own needs. In the decision making aspect of the process, consideration of the real energy needs of the country and the values of the society must be taken into account.

Several studies have been undertaken in recent years on the environmental effects of fuel chains. These studies provide a basis for a generally accepted framework for comparative assessments and for identifying major technical issues and uncertainties in the process. Examples of relevant studies include Refs [2–21]. The studies have been useful in that they have attempted to identify, quantify and, to the extent possible, determine the economic value of health and environmental impacts and also to determine which impacts are usually internalized by corporate and/or government policy. In this manner, they have been useful in helping to place a good number of environmental risks in perspective. They have also helped to highlight key potential impacts associated with fuel chains and, as such, could be of value in

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[1] The expression ‘fuel cycle’ is often used interchangeably with fuel chain, particularly in the nuclear industry. Historically it was planned to ‘cycle’ nuclear fuel through a breeder reactor until all the ^{238}U had been converted to ^{239}Pu and burned. The word ‘chain’ used here is more precise because it is not implied that the chain is, or need be, closed. The phrase ‘energy chain’ is also commonly used. For example, the coal fuel chain includes coal mining and processing, transportation, electricity generation and distribution, and waste disposal. Depending on the scope of the study, the time dimension may also have to be considered. Analysis may include all phases in the lifetime of the power plant and associated or selected facilities, such as construction, operation and decommissioning.

prioritizing mitigation requirements and determining optimal options. In addition, the studies have drawn attention to areas where there exist insufficient scientific and economic data to estimate health and environmental impacts with a high level of certainty. Finally, the studies have been instrumental in showing where further research is needed.

1.2. RATIONALE FOR COMPARATIVE RISK ASSESSMENT

The first reason for comparing risks might be to decide between two possibilities for achieving the same desired end, here considered to be the production of electricity. Assessing health and environmental impacts associated with different energy systems through the use of a framework which facilitates comparison will permit consistent and transparent evaluation of these energy alternatives.

However, there is another reason which is as important or more important: to aid in the understanding of an unusual type of risk by comparing, or contrasting, it with a more common type of risk. This is valid whether or not the energy alternative uses the same technology at another site or a completely different technology.

In this process it is useful to compare the risk at any intermediate stage of the comparative assessment. Thus, one might compare the different effects of an energy system upon health before any attempt is made to put them on a common, usually monetary, metric. Deaths within a month of an accident or in usual operation (prompt deaths) can be compared; and any latent deaths (e.g. cancer deaths 30 years after a nuclear accident) might be compared with deaths occurring long after exposure to air pollutants as lung function is reduced. One might also contrast the importance of life cycle analysis for low energy density systems, such as solar or hydro power, with its lesser importance for high energy density systems.

In general, assessment and integration of information on health and environmental impacts may contribute to:

- More informed decision making, on the basis of better information on potential environmental implications of alternative energy systems;
- Improvement of environmental quality, by helping in the identification of optimal areas for reducing emissions/effluents, etc., on the basis of a comparative assessment of environmental effects associated with alternative supply and demand side management options;
- More explicit consideration of environmental effects within a broader decision making process;
- Education of utilities and the public in environmental matters;
- Influencing of international environmental policy.

1.3. OBJECTIVE

Evaluations of renewable and conventional energy options should be made on the basis of comparable conditions and assumptions. In that regard, this report provides general information, and the benefit of previous experience, to governments, utilities and other organizations that need to undertake comparative assessments of the health and environmental impacts of electricity generation options.

The report provides a checklist and hints to assist analysts in assessing the environmental impacts of electricity generation options. It also alerts the reader to key methodological issues which must be considered when attempting to identify, quantify, value and compare these impacts.

To achieve this objective, the report provides general guidance on:

- Steps that can be taken to identify and estimate health and environmental impacts associated with electricity generation options;
- A method for comparing various technology options on the basis of their health, environmental and other impacts;
- Contentious methodological issues, including the major positions taken.

However, the report is not intended to be a detailed manual on the methodologies available for conducting environmental assessments. In addition, it is not the intention to present detailed guidelines on strict scientific risk assessment (i.e. the product of probability and consequence), but rather to provide information on how environmental risk data (where quantitative data are available) can be considered along with other environmental information that sometimes is not quantifiable in purely scientific terms.

In the more limited realm of calculation of accident probabilities (probabilistic safety assessment, PSA)[2], most experts insist that the primary usefulness of performing the calculation is to help the assessor to understand the system, and either to make safety improvements or to ensure proper operation. In the wider realm discussed here, the analogue is that the comparisons and other aids to understanding must be brought to the attention of the decision maker, together with assumptions, uncertainties and omissions, so that the decision maker may easily understand the problem in limited time.

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[2] Probabilistic risk analysis is normally used interchangeably with probabilistic safety assessment. The latter term is increasingly being adopted and is used in this report.

1.4. SCOPE OF REPORT

This report provides an overview of the methodological approach which has grown out of recent major research efforts. A growing number of electrical utilities are using this approach to identify, quantify and, where possible, place an economic value on the environmental effects associated with electricity supply and demand side management and transmission options. The approach facilitates comparisons and trade-offs of alternative options on the basis of an assessment of impacts and a ‘valuation’ that takes into account multiple criteria for impact comparison.

The report discusses both energy production systems that are not sustainable over a very long prospect and the possible energy sources and systems which are renewable and therefore considered sustainable in the long term. One of the important tasks of society is to find a path from the present power systems which are not sustainable to sustainable possibilities of the future. However, the determination of this path is beyond the scope of this report.

1.5. STRUCTURE

The report is organized as summarized below:

- Section 2 provides the definitional framework for the methodology that follows, covering concepts such as emissions, health and environmental impacts, fuel chains, impact boundaries and life cycle stages.
- Section 3 provides an in-depth discussion of the steps in estimating the health and environmental impacts of electricity generation technologies through the use of the impact pathway, or damage function, approach. The section primarily summarizes the results of recent studies which have focused on evaluating the environmental and economic impacts of fuel chains. It also discusses some aspects of the scope and goal of an assessment which should be considered when beginning an assessment.
- Section 4 provides an overview of methods which can be used to compare electricity generation technologies on the basis of environmental damage, and of possible approaches to integrating environmental considerations with other criteria in planning and decision making processes.
- Section 5 provides a discussion of key methodological issues associated with identifying, assessing and integrating health and environmental concerns. These issues include how to treat uncertainty, risk, the discounting of future impacts, transferability of the results of previous studies, and thresholds.
- Appendices I and II provide discussions of global climate change and energy security, respectively.

2. IMPACTS AND IMPACT ASSESSMENT: BASIC CONCEPTS

2.1. INTRODUCTION

In contrast to the obvious benefits of the provision of electricity, there are also a number of disadvantages due to the detrimental effects of electricity generation on the environment. Some of these impacts (such as smog) are highly visible, while others are not, but many of them are damaging to humans, materials, flora and fauna. Some impacts start even before the construction of a power plant and some continue long after the plant is decommissioned. These harmful effects all have a cost associated with them, a cost which is often not included in the cost of electricity generated but which is nevertheless a cost to individuals as well as to society. It is increasingly being realized that the choice of the type of power plant to build and operate must involve an assessment of its impact on the environment. The effect of a power plant on the environment varies from one type of plant to another, and from region to region. Any comparison between plants must take these variations into account.

The purpose of Section 2 is to introduce some of the key concepts that are used throughout this report. These concepts are fundamental to the general methodological approach that is described.

2.2. FUEL CHAIN

The choice of a particular power plant technology should take into account the full consequences of adopting that technology. Thus, not only must the impacts from the operation of the plant be analysed, but the environmental impacts that occur both before and after electricity generation must be included as well. For example, for a coal fired power plant the full fuel chain, from the extraction of coal from the mine to the disposal of the ash and final decommissioning of the power plant, should be taken into account in an assessment of the impacts of the plant. Included among the impacts are those from the construction of the plant (e.g. deaths and injuries during construction) and the impacts of the production of all materials used in the construction. The impacts of a fuel chain also include all those associated with exploration and development, if a new mine is needed, and with transporting the fuel.

The phrase “should be taken into account” in the previous paragraph means that analysts should be satisfied that all of the important discharges and other factors that could significantly affect health and the environment have been considered. This does not mean that they should analyse every possible discharge and impact in detail — in fact, as discussed in Sections 3.1–3.3, they should not. Nor does it mean that the same types of impacts will always be important for every fuel chain — they will not. However, it does mean that analysts should (at least) satisfy themselves that they have considered every part of the fuel chain that may lead to significant impacts. Some of these impacts may be difficult to quantify. For example, the waste from a coal fired plant, particularly the ash, may be an important problem. Its impacts are difficult to estimate but analysts should nevertheless try to assess whether they are significant.

The inclusion of the impacts of the production of all the materials used in the construction of a plant is a daunting task. However, by wise use of previous studies it is possible to limit the main analysis to those materials which are the main contributors to the impacts. Thus, for a coal fired plant sometimes only the steel and concrete used in construction are considered, since items such as copper and glass are minor contributors to the overall impact.

In the case of a nuclear power plant, impacts would include those associated with uranium mining and conversion, production and transport of fuel elements, plant construction, and storage of spent fuel and radioactive waste for the full term of safe keeping. Also included would be other impacts of the full fuel chain, such as those from steel and concrete production.

In the case of a hydropower, solar power or other renewable energy plant, the energy density of the fuel is less than that of nuclear fuel or coal, and the materials used in construction become a more important, and in some cases the most important, part of the total impact. The manufacture of these materials results in discharges whose impacts must be carefully considered. Impacts can include accidents during construction and production of materials as well as impacts from ordinary emissions. While it is tempting to omit consideration of materials used in construction for both coal fired and nuclear plants, it is often worth while to include them to facilitate and illuminate a comparison with renewable, low energy density systems. Also, analysts should make sure that there are no materials constraints for rare metals, which may lead to concerns about depletion or security of supply.

Figure 1 shows a set of reference energy (fuel) chains.

2.3. EMISSIONS AND OTHER BURDENS ON THE ENVIRONMENT

One major type of effect of power generation on the environment arises from emissions from the power plant or from other parts of its fuel chain. These emissions include solid, liquid, gaseous and radioactive emissions. In a broad sense, the effects of power generation also involve aesthetic factors (such as the visual impacts of the power plant and transmission lines), physical effects (such as increased ground pressure due to the construction of a dam) and discharges such as noise.

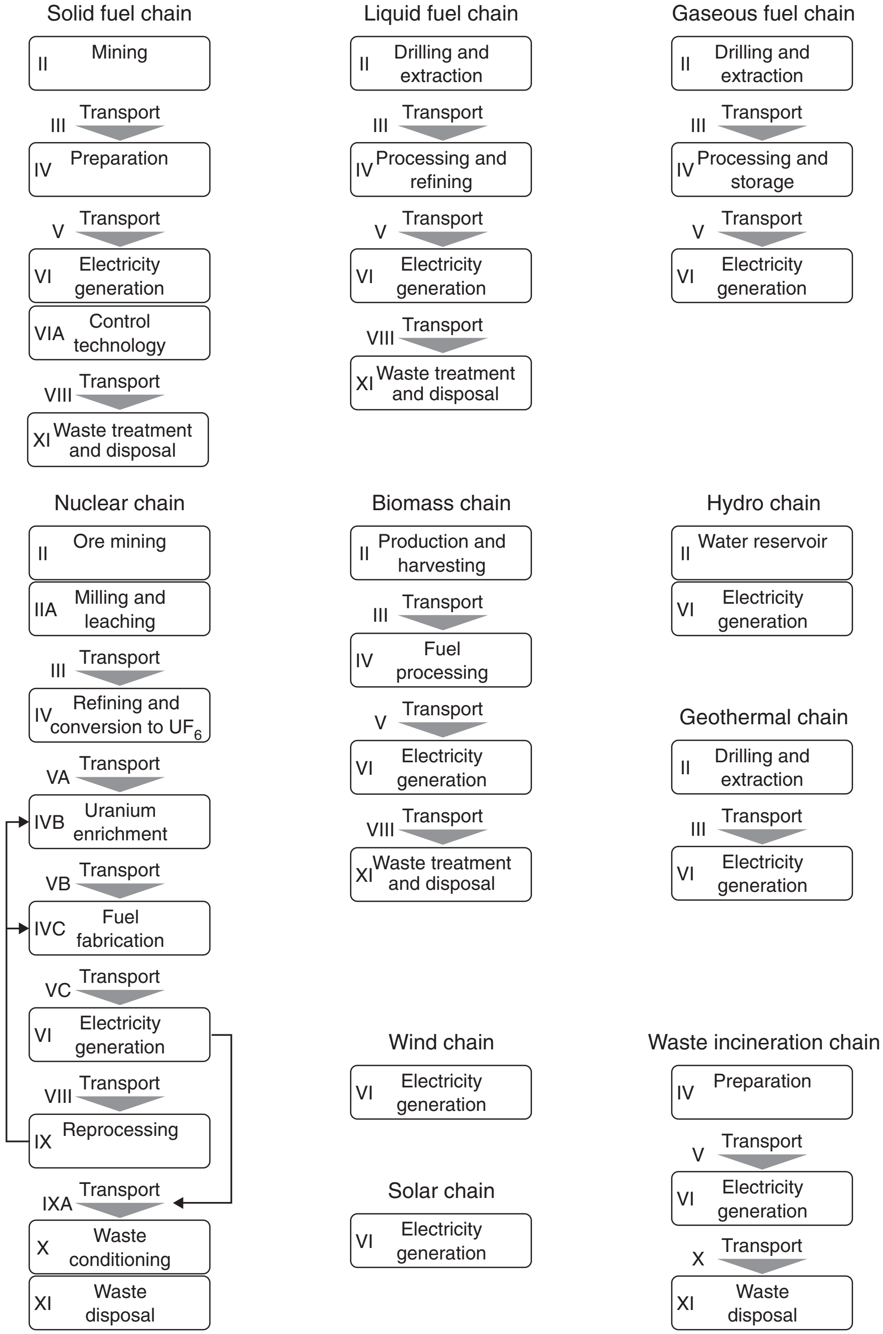

FIG. 1. Reference energy (fuel) chains. Every electricity generation step contains a construction stage, an operation stage and a decommissioning stage.

Examples of common emissions and wastes from power plants themselves include the following (a more extensive discussion is provided in Section 3):

(a) Fossil fuelled plant

- *Gaseous:* sulphur dioxide, oxides of nitrogen, hydrocarbons, carbon monoxide and carbon dioxide.
- *Liquid:* wastewater.
- *Solid:* particulates emitted from the chimney stack, which remain suspended in the air and are transported like a gas, and solids collected as ash from the plant.
- *Secondary:* in addition to the direct emissions, there are secondary components produced in the atmosphere from chemical reactions between the emissions and other substances in the atmosphere. These secondary pollutants include ozone formed from the oxides of nitrogen and volatile organic compounds (VOCs), sulphate particles formed from sulphur dioxide, and acid rain formed from sulphur dioxide and oxides of nitrogen.
- *Other:* other burdens include aesthetic aspects such as the visual ‘intrusion’ of the plant itself, noise, smoke and heat rejection from the cooling circuit.

(b) Nuclear power plant

- *Gaseous:* radioactive off-gases.
- *Liquid:* radioactive water effluent.
- *Solid:* radioactive spent fuel elements, and chemicals from allied plants such as demineralizers.
- *Other:* aesthetic aspects and heat rejection.

(c) Wind power plant

- *Other:* noise and television interference from wind turbines.

The emissions mentioned above are the normal emissions from the plant itself during operation, but there are also important environmental impacts from other parts of the fuel chain and from the construction and decommissioning phases of the plant. In addition to these ‘normal’ releases there are potential releases and other environmental consequences as a result of accidents.

Particularly for low energy density plants such as hydro, wind and solar, analysts should consider emissions in the course of construction and maintenance. For these types of fuel chains, such indirect or secondary emissions may be a large percentage of the total emissions from the fuel chain. There is inconclusive evidence about whether they constitute a large amount, in absolute (rather than percentage) terms, compared with the emissions from conventional, fossil fuelled plants.

2.4. IMPACTS

Emissions themselves are not necessarily an issue, but it is the effect of these on the environment that is important. For example, inhalation of air containing raised levels of sulphates in combination with certain other emissions can increase the probability of premature death. While sulphur dioxide can be beneficial, in that it can increase growth of certain plants at low concentrations, it can decrease growth at higher doses. In combination with water, sulphur dioxide forms acids which have a corrosive effect on a variety of materials.

Since an impact is influenced by the concentration of an emission, the method by which emissions are dispersed in the environment is important. Thus, for emissions into air the height at which the release occurs, the turbulence of the atmosphere, the distance to the receptor (i.e. the human population, animal and plant species, ecosystems or materials that are affected), the topography between the emitter (i.e. the source of the emission) and the receptor, and meteorological factors are all important.

The pathway between emitter and receptor can be complicated. For example, liquid effluents released into rivers will be diluted but then can be concentrated by means of biological action and can reach a human receptor through a complicated food chain. Furthermore, gaseous emissions can influence the resistance of crops to attack by insects or to disease, resulting in reduced yields. Thus, it is important to evaluate all significant pathways between emissions and their impact.

Impacts can be divided into those affecting human health, animal health, flora and materials. In turn, human health effects can be subdivided into those that affect the operators of the plant (occupational effects) and those that affect the population at large (public health effects). Estimates of impacts due to an emission are usually based on a dose–response relationship. Such relationships have been evaluated for a number of pollutants, for a range of receptors and for different health effects (health end points). However, no dose–response functions are available for some impacts and thus other methods, such as the critical loads approach (Section 3.6.1.3), may have to be used.

2.5. INDICATORS

In order to facilitate the comparison of environmental effects of different energy options, there is a need for consistent, quantitative indicators of environmental impacts. The need for such indicators can arise in many different contexts, such as:

— Choice of technologies,
— Choice between alternative fuel cycles that use the same generation technology,
— Assessment of impact trends with time,
— Comparison between alternative pollution abatement technologies,
— Impact comparison between economic sectors,
— Impact comparison between different regions.

Primary indicators of health and environmental impacts are estimates of the specific effects themselves (as discussed in Section 2.4), such as increased rates of respiratory illness and damage to trees. Other indicators are often informative surrogates for these effects, particularly when they are difficult to estimate directly. The magnitude of pollutant emissions (and of other types of burdens) is one type of indirect indicator (e.g. tonnes of sulphur dioxide emitted).

Analysts may also wish to categorize these indirect indicators according to the geographical impacts (see also Section 2.6):

— Global effects due to
  - Change in concentration of greenhouse gases;
  - Long lived radioactive substances.
— Regional, local and site specific effects from
  - SO_2, NO_x and particulates;
  - Heavy metals;
  - Radioactive gases;
  - Liquid and solid wastes containing toxic or radioactive material.

However, it must be recognized that indirect indicators are often only shown to be a good surrogate in particular situations and cannot be used generally.

It is common to consider mortality as the primary end point for health effects. This is because there is much greater concern for injuries or health effects that are fatal. However, analysts should also consider other important health end points, i.e. non-fatal injuries and morbidity. There are dose–response functions for many of these (Section 3.6.1).

Damages, expressed in economic terms, are a useful summary indicator. Analysts should also be aware that there are other useful indicators that supplement the type of information provided by economic measures of health effects. These other indicators provide information on the amount of time for which an individual’s health is affected:

— Loss of life expectancy (LLE),
— Working days lost (important for an employer),
— Public days lost (important for the employee).

Ordering of impacts by magnitude can be different when these indicators are used. For example, a radiation induced leukaemia occurs within a few years after irradiation and can lead to an LLE of 30 years and many working days lost. A radiation induced ‘solid’ cancer occurs later, and the LLE may be only 5 years, often after retirement, with no working days lost but some public days lost. Acute episodes of air pollution can lead to prompt asthma attacks, and even loss of life with an LLE of 40 years. More insidious is the delayed effect of deterioration of lung function which can occur late, with relatively few years of lost life. Accidents can also lead to prompt deaths with an LLE of 40 years.

2.6. BOUNDARIES

There are two further considerations when carrying out an impact assessment and these refer to the boundaries within which impacts are considered. Firstly, there is the temporal boundary, which is chosen to include the period during which most of the impacts take place. This period can be classified as short term (one to three years), medium term (a human generation) or long term (many generations). Thus, for nuclear and coal fired power plants, where long lived radionuclides or other carcinogens are emitted, the risk of cancer often only becomes apparent after many years (medium term) and the effect of any postulated genetic damage to the population (if present) will only manifest itself over many generations. Air pollution is expected to show both short term ‘acute’ effects (after one or two weeks) and effects at the end of a lifetime (medium term).

The periods during which impacts are determined include pre-operational effects, such as environmental effects associated with exploration and mine construction, and post-operational effects, such as those which will be experienced during long term storage of spent nuclear fuel.

Secondly, there is a need to set a physical boundary around the plant and the associated fuel cycle, within which the impacts will be studied. Such a boundary can be classified as local (up to 100 km), regional (100–1000 km) or global. Local impacts include the effects of emissions acting on the immediate neighbourhood of the plant. However, a gaseous plume can have an effect many hundreds or thousands of kilometres downwind and can involve transformations during the downwind movement making a regional or global impact. Thus, atmospheric chemistry involving emissions of sulphur dioxide and nitrogen dioxide can produce acid rain, leading to tree damage, in distant countries. The emission of carbon dioxide, on the other hand, contributes towards global climate change, and each fossil fuelled plant has an incremental global impact, but the CO_2 emissions do not have a local or regional impact.

A decision has to be made concerning the extent to which impacts in distant countries should be included in an impact assessment. For instance, how much of the impact of coal mining operations should be included in an impact assessment of a coal importing country? It is just to enable such complex boundary issues to be discussed logically that analysts attempt to assign a monetary value to the impact.

The choice of boundaries is strongly connected with the societal decision that the study is intended to illuminate. For example, most decisions of electrical utilities are based on local and regional effects only, although the populace often wants to be reassured that the global effects are not overwhelmingly bad, so analysts may also wish to include an assessment with wider boundaries.

2.7. NORMAL OPERATION AND ACCIDENTS

Impacts can be divided into those due to the normal operation of the complete fuel chain and those arising as a result of a severe accident. Severe accidents are rare (i.e. low probability) occurrences but have significant impacts, such as the collapse of a dam wall, a major coal mine explosion, the fire at the Chernobyl nuclear power plant or the Exxon Valdez tanker oil spill. The expectation of the impact, or average impact, of such accidents has to be evaluated using probabilities and taking into account the major factors in the complete causal chain that can lead to the accident. The term ‘risk’ is also used in connection with the expectation of the impact: risk = $\Sigma f_i x_i$, where f_i is the frequency of the accident and x_i is the associated consequence; index i represents the type or severity of accident. In impact assessment, interest is in the expected impact, not just the probability of an accident.

The impact (actually, the expected impact) of an accident is defined in terms of the probability of occurrence multiplied by the damage that it would do if it occurred. There is, however, an additional factor that has to be considered, namely, the distinction between risk to an individual and risk to the population. There is also the question of the perceived risk associated with the event. Thus, some individuals think nothing of mountain climbing or parachuting, but associated with these activities are voluntary risks that they are prepared to take. On the other hand, an industrial risk, such as that of an accidental radioactive release, is an involuntary risk and one which people are not as prepared to accept. An event with a low frequency of occurrence, but with a high impact, is perceived[3] to be more severe than an event that has a high

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[3] This perception varies from individual to individual. Someone whose spouse and child have been killed in a car crash is likely to consider the total of small accidents of this kind to be more important than one large accident. The crash of a private aircraft that kills everyone in a large family is not perceived by society to be as bad as that of a commercial aircraft killing the same number of people in many families, possibly because there are fewer survivors to grieve. Societal perception, as evidenced for example by newspapers, emphasizes large accidents, which are what analysts must usually consider.

frequency but a low consequence, even if the mathematically calculated expectation values of the risks are the same. For instance, an aircraft crash with many deaths is seen as a more serious occurrence than a large number of car crashes with a relatively small loss of life per accident.

2.8. STANDARDIZATION OF MEASURES

The size of plants and their reliability and availability can be different. In order to be able to compare the impacts from different technologies, or from similar plants in different regions, it is preferable to place the impacts on a common basis, to the extent possible. The common method of standardizing such a situation is to relate the impact (or impact indicator) to a common unit of energy (the kilowatt-hour (electric)) produced. Thus, the amount of sulphur dioxide emitted per kW(e)·h from one plant can be compared with that from a plant of another type or size. Similarly, the expected increase in premature mortality or physical disabilities over the full life cycle of the complete fuel chain can be compared for two different plants.

However, there are a number of problems when trying to compare a range of impacts from different plants. For instance, how does one compare health risks such as mortality and morbidity, or how does one compare the effect of oxides of nitrogen with the effects of sulphur dioxide? In order to bring these different impacts to a common denominator, attempts have been made to express all the impacts in terms of a common unit of cost, or economic damage. Thus, the effect of an air pollutant on the growth of crops can be estimated in terms of the change in yield and the monetary value of the loss in a cash crop. Similarly, the costs of an expected (in a statistical sense) mortality and morbidity can be considered if their monetary value can be estimated. The economic valuation, or 'monetization', of human health is controversial, though for economists it is widely accepted (Section 4.2.2). The monetization of impacts is neither easy nor always possible. Certain impacts cannot be readily calculated or expressed in monetary terms. For instance, the precise impacts of global climate change are very contentious.

Depending on the scope of the study, an analyst may also wish to estimate the externalities associated with fuel chain options. Externalities are effects on the well-being of individuals and firms that are not reflected in electricity market decisions, i.e. in the prices of electricity and the fuels used to generate it. Being an economic concept, externalities are measured in economic terms. For example, occupational injuries from fuel chain activities are a type of impact; the economic values of these injuries are a standardized measure of their 'costs' or 'damages', and the part of these damages that is not compensated (e.g. through higher wage rates) is known as the external costs.

One further problem connected with the determination of external costs is that associated with the valuation of impacts in the future. What is the cost of an impact at some time in the future compared with the cost of that same impact now? Normally, a discounting rate is applied to offset a future cost against a cost in the present. However, the determination of a discount factor has been controversial, particularly in connection with intergenerational impacts (Sections 4.4.1 and 5.2.4).

2.9. OTHER IMPACTS

The impacts considered so far have referred to the effects of the various solid, liquid, gaseous and radioactive emissions from a fuel chain. There are a number of other impacts, most of which are difficult to define and quantify. These include socioeconomic effects such as the net loss or creation of jobs, societal effects on communities affected by the operation of the fuel chain, and effects on regional and international trade. There are also a number of aesthetic impacts, mentioned in Section 2.3, such as the visual impact of a power plant and the impact of reduced visibility due to power plant emissions. Where such effects cannot be quantified, an impact assessment should include a subjective but well informed comment on each of the relevant items.

3. METHODOLOGICAL APPROACH FOR ESTIMATING HEALTH AND ENVIRONMENTAL IMPACTS

3.1. OVERVIEW

3.1.1. Introduction

The purpose of Section 3 is to suggest how to estimate the major health and environmental impacts of electrical power generation. As previously discussed, this report primarily summarizes recent developments in studies of the impacts, economic damages and externalities of fuel chains. As such, the material in this section draws heavily on these studies, especially Refs [2–21].

An important feature of any particular method is that it helps analysts ensure that they have considered and discussed any relevant or important environmental release and its impact, and that they have presented their results as clearly as possible. Therefore, the methods described in this section complement, but do not replace, other methods used in environmental impact assessments, environmental impact statements, ecological risk analyses, health risk analyses, life cycle assessments, environmental management, PSAs, comparative risk assessments and other, related methods and procedures. In fact, as discussed in Sections 3.1.2–3.1.4, many of the methods described in this report can be used in these types of studies.

The general methodological approach described in Section 3 is based on the impact pathway, or damage function, approach. However, the guidance in this report extends beyond that approach. It refers to relevant parts of other methodologies and includes: methods and issues related to estimates of impacts using a common economic metric; the integration of results; and analysis when impacts cannot be quantified.

The remainder of Section 3 describes this general approach for estimating health and environmental impacts. Sections 3.2–3.6 describe the basic steps for making these estimates. Section 3.7 describes some methods for accounting for the uncertainty in estimates of impacts. Section 3.8 provides suggestions on how to synthesize the estimates of impacts into forms that are more useful for comparative assessments of the options for generating electrical power. At the end of each of Sections 3.2–3.8, a brief summary lists the important types of information and data that are required in that step of the analysis, the type of analysis required, and the type of output or results of that analysis.

The nature and magnitude of health and environmental impacts vary, depending on the type of fuel, the type of power plant and other factors. Section 3 is not intended to be an encyclopedic reference on the methods for estimating these impacts, nor on specific estimates from other studies.[4] Rather, it ‘points the way’ to doing an impact study by providing basic information on important concepts and methods, and suggestions on how to carry out such an analysis, as well as references to publications that contain detailed descriptions and applications of these methods.

3.1.2. Impact pathway (damage function) approach

Impacts of fuel use on health have been noted for centuries. Possibly the earliest reference to such impacts was an order from King Edward I of England to the Sheriff of Surrey on 12 June 1307 to stop the burning of ‘sea-coales’ (coal). However, systematic studies began with the nuclear industry in the 1960s [22, 23] and were extended to other technologies (fuel chains) in the 1970s.

Wilson [24] pointed out the need for a common metric in comparisons of energy systems. By restricting the energy system to electricity generation, a common

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[4] The Database on Health and Environmental Impact of Energy Systems (HEIES), developed by the IAEA, contains numerical estimates of the health and environmental impacts of electrical power production as obtained in other studies (see Table II [17]).

denominator is easy to establish and one may describe the impact per kW(e)·h. To help in ensuring that all impacts of an energy system are considered, Pigford [25] prepared charts for the flow of materials through the fuel chain. Analysts are urged to examine typical generic flow charts as an aid to understanding the importance, or lack of importance, of the various emissions. Hamilton [26] used such flow charts in a set of systematic studies of the health and environmental effects of various energy systems. These and other studies of the period were well summarized at a conference in Paris in 1980 (Colloque sur les risques sanitaires des différentes énergies).

The authors mentioned in the previous paragraph deliberately avoided the thorny question of the economic cost of such impacts. This was being addressed during the 1970s and 1980s by various economists and decision theorists. Raiffa et al. [27] wrote a seminal paper on discounting of health risks, and Barrager et al. [28] and Lave and Silverman [29] discussed other economic issues. Okrent [30] and Wilson [31, 32] related the risk–benefit problem to other, wider problems in society. Also in the 1970s, various authors pointed out that comparisons are different if different boundaries are used for analysis. Particularly for solar, wind and hydro power systems, the materials used in construction add to the impact and a full life cycle analysis incorporates these effects. Many of the concepts discussed in this report stem from these earlier studies, and in particular it is often useful to halt, for example, at health impacts and to make a comparison at that point before proceeding to monetary valuation.

Hohmeyer [33] in Europe and Ottinger et al. [34] in North America popularized the notion that externalities and social costs result from electrical power production and emphasized putting the impacts into monetary terms. These two studies have been widely criticized for an unnecessarily naive and incorrect analysis of nuclear accidents and an inconsistent comparison with air pollution. However, they laid additional groundwork for, and inspired, the major studies that took place in the early 1990s [2–21]. These studies are the forerunners of the many recent studies on this subject (e.g. Refs [35–46]). An important review of many of them has been made by the Office of Technology Assessment of the United States Congress [47].

The general approach described in Section 3 for estimating these impact indicators builds upon all of these studies and in particular their contribution to the development of the impact pathway (damage function) approach. Studies in Europe [2–7] and North America [8–21] follow this approach, which is close to becoming a standard. Some of the advances made in the more recent studies include:

- An explicit life cycle perspective and a consideration of the fuel chain, rather than of the emissions from electrical power generation alone;
- More thorough engineering analysis for estimating emissions from power plants, rather than relying on previous estimates or generic estimates;

- Greater use of atmospheric dispersion models to estimate spatial concentrations, rather than aggregate analyses and assumptions;
- Extensive consideration of many different impact pathways;
- Greater attention to the concept of externalities, as distinct from costs or damages;
- Emphasis on the uncertainty in the estimates and on their site dependent nature;
- Extensive use of recent literature on dose–response functions and economic valuation functions.

3.1.3. Summary of impact assessment methodology

The impact pathway approach is the crux of the impact assessment methodology described here. The impact pathway approach is a bottom-up method for estimating impacts (Sections 5.2.2 and 5.3.2 present related discussions). The fundamental idea of this approach is to track the path of events from the fuel chain activities to their emissions, to the changes in the ambient concentrations of the pollutants and then to the incremental impacts that result from these concentrations. Many recent studies also estimate the costs of these impacts and the extent to which these costs are not reflected in electricity prices, and include these steps in the analysis as part of the impact pathway approach. In this report, however, economic valuation and externalities are considered separately, as part of a broader methodological approach for doing comparative assessments of electrical energy systems (Section 4).

The tracking of emissions, pollutant concentrations, environmental impacts, costs and externalities is done for a specific power plant site (either real or hypothetical) with actual data on emissions, affected populations, etc. The time frame over which the assessment is made should cover the full effects of a fuel chain. For example, the construction of a generating plant should be included in the analysis, as should its decommissioning. In order to relate these costs to the electricity generated, it is necessary to consider the amount of electricity generated by the plant over its lifetime. Thus, the health and environmental impacts of concern are those that result over the lifetime of the plant, as well as impacts that occur well after the plant ceases operation and is decommissioned.

The impact pathway approach, as adapted from Refs [2, 8, 10], consists of three major steps of analysis:

- Characterization of fuel chain and technology
- Estimation of changes in pollutant concentrations and other risk factors
- Calculation of expected impacts.

These steps can be represented by the following sequence:

Fuel chain activity → Source term → Changes in concentration → Impact

Each step consists of data modelling or analysis. The numerical output of one step is the input data for the next step. The steps are discussed further in Sections 3.4–3.6.

Figure 2 [2] is a conceptual flow chart of the impact assessment methodology described in this section. In some studies, the impact pathway method includes economic valuation (as reflected in the flow chart), but here economic valuation is considered separately from methods for estimating impacts per se. Economic valuation is one of several methods for translating estimates of impacts into some other unit of measurement that facilitates comparative assessment. These methods are discussed in Section 4.

The subsections of Section 3 correspond to the steps of the impact pathway methodology:

(1) Definition of scope
  — Specification of scope
  — Identification of resources needed
(2) Initial screening analysis
  — Fuel chain activities
  — Identification of priority impact pathways

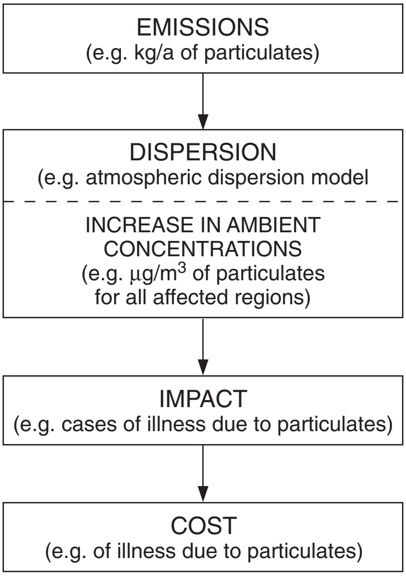

FIG. 2. Flow chart of impact pathway method [2].

(3) Characterization of fuel chain and technology
    - Technology description and magnitude of fuel chain activities
    - Type and magnitude of emissions and other residual burdens
    - Data on receptors and the environment
(4) Estimation of changes in pollutant concentrations and other risk factors
    - Important considerations
    - Changes in concentrations of primary airborne pollutants
    - Radionuclides
    - Secondary airborne pollutants
    - Accidents
    - Freshwater pollution modelling
    - Other changes in environmental conditions
    - Simplified methods
(5) Calculation of expected impacts
    - Basic approach for calculating impacts
    - Impacts on human populations
    - Impacts on the natural environment
    - Accidents and risks
    - Perceptions of impacts
    - Global climate change
    - Energy security
    - Other impact indicators
    - Impact parameters
    - Accounting for future changes
(6) Uncertainty and sensitivity analysis
    - Sources of uncertainty
    - Providing information on uncertainty
    - Identification of key results
(7) Synthesis of results.

The impact pathway analysis per se comprises steps 3–5. Steps 1 and 2 are the preparatory steps in implementing an impact pathway study. Steps 6 and 7 synthesize and interpret the results of the impact pathway calculations.

A major characteristic of this approach is that it sets priorities to consider the more important impacts in detail and the less important ones in much less detail. There are two major reasons for this prioritization. The first is that any study will have resource limitations. Thus, it is impossible to do a thorough study of every possible impact that arises in fuel chains, simply because of time and budget constraints. The second reason is that the empirical evidence thus far strongly indicates that, in a given fuel chain, most of the health and environmental impacts can be attributed to relatively few factors and their associated environmental pathways.

TABLE I. DATABASES WITH INFORMATION ON FUEL CHAIN DISCHARGES

Name	Description
CO_2 Technology Data Bank (International Institute for Applied Systems Analysis (IIASA))	The IIASA databank is very comprehensive in its coverage of technologies and CO_2 emissions. Its scope is limited primarily to CO_2 emissions (no information on air transport or impacts). Data coverage includes: general data on estimated date of availability of each technology, life cycle definition and position in the fuel cycle; technical data on unit size, availability, operating lifetime of power plant, energy inputs and outputs, and efficiencies; economic data on investment costs, operation and maintenance costs, decommissioning costs and fuel costs; environmental data on definitions of pollutants and emissions; and fuel cycle information on energy use per unit of output, costs per unit of output, emissions and market penetration (the last being based largely on expert judgement). The databank allows analysts to select technologies, calculate their efficiency, and consider the costs and environmental effects of energy conversion chains from resource base to end use. It gives qualitative and quantitative technology descriptions for CO_2 reduction purposes. The number of technologies covered is about 1600
Databases and Methodologies for Comparative Assessment of Different Energy Sources for Electricity Generation (DECADES) (IAEA)	The objective of the DECADES project is to improve the ability to make comparative assessments of different fuel chains for electricity generation in planning and decision making. The main databases have information on the technical parameters, economic characteristics and emissions of all major electricity generation technologies. Generic or reference data are provided, as are data that are country and vendor specific. The databases also have documentation on the data sources. Plans are to have databases on dose–response relationships, health and environmental impacts, and the effects of pollutants
ECOINVENT (Swiss Federal Institute of Technology, Paul Scherrer Institute)	ECOINVENT was developed to provide environmental inventories of energy systems and energy products to support life cycle assessment of generic products, and for application in comparative studies of energy systems. It reflects primarily the present average conditions in Switzerland and in the countries of the Union pour la coordination de la production et du transport de l’électricité. The database contains the relevant

TABLE I. (cont.)

Name	Description
ECOINVENT (cont.)	unaggregated, transparent and consistent data on material balances for a wide range of energy systems: coal, oil, natural gas, nuclear, hydro, biomass (wood), solar thermal, geothermal and photovoltaic. All energy systems are analysed using the 'cradle to grave' approach, including all steps in the chains and all phases in the life cycle of each process: production of infrastructure and materials, transport, construction, operation and maintenance, dismantling and waste treatment. Approximately 500 interconnected processes have been investigated. A very broad spectrum (about 300) of energy and non-energy resources as well as air and water pollutants and solid wastes has been covered. Land depreciation and waste heat are also accounted for. A recent extension of ECOINVENT includes environmental inventories for future (i.e. advanced) electricity supply systems for Switzerland
Energy and Power Evaluation Program (ENPEP) (Argonne National Laboratory (ANL))	ENPEP is primarily used by the ANL in its energy planning work for developing countries. The data in ENPEP are principally from work done by the ANL for the US Department of Energy on energy technologies and emissions. Data from the Environmental Protection Agency and the Electric Power Research Institute are also used. The ENPEP structure is distinguished from most other systems in that data on fuel cycle activities, energy technologies and pollution abatement technologies are in separate files. This structure allows ENPEP users to build a scenario from any combination of fuel cycle activities, energy technologies and pollution abatement technologies. Also, unlike most of the other systems, ENPEP is an integrated energy modelling system, not just a database and information system. The core of this system is a general equilibrium energy markets module
Environmental Database (EDB) (United Nations Environment Programme (UNEP), Stockholm Energy Institute, Tellus Institute)	EDB is used by UNEP primarily in developing countries. It is also used by the Tellus Institute, which has done recent work on externalities. EDB and its companion information system, the Long-range Energy and Environment Alternatives Planning Model (LEAP), are proprietary. Like many of the databases of this type, EDB's primary data sources are from the ANL report [48] used by ENPEP, the Electric Power Research

TABLE I. (cont.)

Environmental Database (EDB) (cont.)	Institute and the Environmental Protection Agency. For European data, EDB relies heavily on the inventory of air polluting emissions provided by the European Environmental Agency programme CORINAIR. EDB covers the fuel cycle for all major fuels and technologies. EDB can be thought of as a two dimensional matrix in which the rows represent the sources of emissions and the columns represent the specific emissions and the direct occupational health and safety effects. Like most of the other databases, EDB is ‘not fully populated’, i.e. there are no data for many of the cells of the information matrix
Instrumente für Klimagas-Reduktions-Strategien (IKARUS) (Fachinformationszentrum Karlsruhe)	IKARUS is an ambitious system in terms of its coverage of individual technologies (about 10 000 are included). The database has information on type of technology, nominal capacity, year of start of operation, location, inputs and outputs, energy efficiency, time/availability ratio, investment costs, taxes, fixed and variable operating costs, emissions, radiation level, noise level, inventory and literature documentation. IKARUS uses linear programming to determine minimum cost technological options, subject to emissions constraints
Total Emission Model for Integrated Systems (TEMIS) (R. Fritsche, Öko-Institut)	TEMIS has been favoured by several US Department of Energy offices and national laboratories in their fuel cycle analysis activities. Like ENPEP, EDB and the CO_2 Technology Data Bank, TEMIS takes into account all activities within a fuel cycle. However, TEMIS is distinguished by its ability to include secondary effects, e.g. CO_2 emissions associated with the production of the steel that goes into the construction of a coal fired power plant

However, analysts must beware of omitting important potential impacts that are sometimes neglected because the specific health effect has not been identified or is speculative. The effect of fine particles, discussed later, is an example of an effect which was omitted or downplayed in many previous bottom-up studies.

Thus, although analysts will not be able to address every possible impact in detail, they should omit an impact from analysis only with great caution. If an impact is thought to be small, then it may be appropriate to make pessimistic simplifying assumptions that overstate the impact but that demonstrate that it is small. On the other hand, if an impact is thought to be large or, for whatever reason, of great significance, then it should be analysed to the extent possible.

For example, if a nuclear plant is an option, then a detailed study would certainly be necessary because the nuclear industry is held to a higher standard by regulatory agencies and by the public in general. However, if nuclear power were not really an option but it were considered desirable to provide information on nuclear fuel chains just to 'round out' the report, then a simplified review of previous studies could be included. In this situation, a simple historical calculation of the world's average nuclear accident probabilities, combined with a pessimistic estimate of the effects of these accidents, may be permissible. The studies reviewed should be of the same type of power plant and analysts should assess whether there is much variation in previous estimates, as well as the major factors responsible for the variation.

Table I lists useful databases with information on the more important discharges from different fuel chains. Table II summarizes the more important discharges from each stage of different fuel chains. Each of these discharges can have one or more pathways that result in a health or environmental impact.

3.1.4. Comparison with related approaches

The impact pathway approach tries to develop quantitative estimates of impacts. Thus, the approach is different from many environmental impact statements or assessments, which are very detailed in qualitatively describing the possible environmental impacts of a project, but which frequently do not focus on quantitative estimates of them. In contrast, the impact pathway approach focuses on aspects of the environment and on impacts that are the most important and that can be quantified in some way, but not on all of the impacts.

The estimates of human health and environmental impacts are based on scientific information and analysis, rather than on generalized statements, anecdotal evidence or the impressions of individuals. This generally means that a bottom-up, rather than top-down, analysis is undertaken. The bottom-up approach provides a more detailed depiction of the processes that are taking place. It is generally preferred to the top-down approach, which is based on aggregate correlations. References [2–21] are examples of bottom-up studies; Ref. [33] is possibly the most well known top-down study; and Refs [34, 49, 50] are examples of bottom-up studies that take an aggregate generic approach (rather than site specific modelling).

In a bottom-up analysis, individual pathways are identified to link the source of the emissions, the dispersion of these emissions, their incremental health and environmental impacts and the economic value of the damage (or, in some cases, benefit). Because of its more specific, detailed nature, the bottom-up approach is able to account for site specific differences that affect the nature and extent of health and environmental impacts. This site specific aspect is also a limitation of the approach in that it is more difficult to make generalized statements of environmental impacts for the purpose of, for example, national energy policy making. In contrast, a top-down analysis begins with an overall aggregate estimate of impacts or damages and allocates the average impact to different sources (such as the fossil fuel energy sector).

The impact pathway approach does not replace, but rather complements and can be used in conjunction with, other methodological approaches. These other approaches include:

- — Environmental impact statements and assessments;
- — Life cycle analysis;
- — Life cycle costing;
- — Life cycle assessment, ecological risk analysis and health risk analysis;
- — Total energy cycle analysis.

Each of these concepts is briefly described below. The description focuses on the similarities to and differences from the impact pathway approach.

Reference [10], (table 4.4.1, p. 4-20) compares the impact pathway approach with the approach that is typically used in environmental impact statements and assessments, which are generally much more detailed and comprehensive in their description of an individual site. They are also generally more qualitative in their discussions of the environmental setting and impacts. They frequently focus on worst case scenarios for the purpose of regulatory compliance. The impact pathway approach, on the other hand, generally focuses on fewer impacts, delineates the pathways that result in these impacts, and attempts to quantify their magnitude by modelling the pathways.

Life cycle analysis is another common approach. In the conventional use of the term, life cycle analysis accounts for the flows of energy and materials in each part of a production process. Life cycle analysis is used in many fields of engineering, such as chemical engineering. Fuel chain analysis extends the life cycle concept. As illustrated in Fig. 3, fuel chain analysis accounts for the more significant processes in each stage of the life cycle (e.g. mining, transportation, power generation and waste disposal). A common distinction between life cycle analysis and the impact pathway approach is that life cycle analysis traditionally restricts itself to accounting for the flows of energy and materials, whereas the impact pathway approach as described in this report takes this accounting as the first step in estimating the impacts of the discharges of materials (e.g. of pollutants) and in this sense encompasses life cycle analysis.

Life cycle costing focuses on the costs of each stage or process in the production. These costs are usually limited to the financial costs of capital investment, operation, maintenance, administration and regulatory compliance. The costs of human illness and damage to the environment that result from the production process

TABLE II. TAXONOMY OF FUEL CHAIN DISCHARGES AND OTHER RESIDUAL EFFECTS

	Coal steam, fluidized bed, integrated gasified combined cycle				Biomass/wood			Nuclear			
	Mining	Fuel processing	Transport	Generation	Harvest	Transport	Generation	Mining	Fuel processing	Transport	Generation
Outdoor air											
Particulates	×	×	×	×	×	×	×	×	×	×	
SO_2	×	×	×	×	×	×	×	×	×	×	
NO_x, nitrate, NO_2	×	×	×	×	×	×	×	×	×	×	
Toxic and metals	×	×		×			×	×	×		
CO	×	×	×	×	×	×	×	×	×	×	
Greenhouse gas/CO_2	×	×	×	×	×	×	×	×	×	×	
CFCs											
Steam				×			×				×
Radioactive	×	×		×				×	×		×
Secondary outdoor air											
Acid aerosols	×	×	×	×	×	×	×	×	×	×	
Acid deposition	×	×	×	×	×	×	×	×	×	×	
Ozone, (HCs, VOCs)	×	×	×	×	×	×	×	×	×	×	
Indoor air											
Surface water											
Chemicals	×	×	×	×		×	×	×	×	×	×
Thermal				×			×				×
Impinge/entrain				×							×
Radioactive	×	×		×				×	×		×
Impoundment											
Consumption	×	×		×			×	×	×		×

Solid waste											
Transport				×			×				×
Volume/land use	×	×		×	×		×	×			×
Hazardous/PCBs											
Toxics in ash				×							
Radioactive: high											×
Radioactive: low				×				×	×		×
Construction/operation											
Construction				×			×				×
Land use/noise/ terrestrial	×			×	×		×	×	×		×
Transmission: land				×			×				×
Transmission: EMF				×			×				×
Explosion/accident	×	×	×	×	×	×	×	×	×	×	
Nuclear accident											×
Spills											
Decommissioning				×			×				×
Use of public facilities			×			×				×	
Socioeconomic	×	×	×	×	×	×	×	×	×	×	×

TABLE II. (cont.)

	Municipal solid waste		Natural gas/oil: combustion turbine, combined cycle, steam				Hydro	Solar, wind		Demand side management	
	Refuse derived fuel processing	Generation	Production	Refining	Transport	Generation	Generation	Manufacture	Operation	Manufacture	Operation
Outdoor air											
Particulates	×	×	×	×	×	×		×		×	
SO_2	×	×	×	×	×	×		×		×	
NO_x, nitrate, NO_2	×	×	×	×	×	×		×		×	
Toxic and metals	×	×	×	×		×		×		×	
CO	×	×	×	×	×	×		×		×	
Greenhouse gas/CO_2	×	×	×	×	×	×	×	×		×	
CFCs								×		×	×
Steam		×				×					
Radioactive											
Secondary outdoor air											
Acid aerosols	×	×	×	×	×	×		×		×	
Acid deposition	×	×	×	×	×	×		×		×	
Ozone, (HCs, VOCs)	×	×	×	×	×	×		×		×	
Indoor air										×	
Surface water											
Chemicals	×	×	×	×	×	×	×	×		×	
Thermal		×				×	×				
Impinge/entrain						×	×				
Radioactive											
Impoundment							×				
Consumption			×	×		×					

Solid waste											
Transport									×		
Volume/land use	×	×									
Hazardous/PCBs								×	×		×
Toxics in ash		×									
Radioactive: high											
Radioactive: low											
Construction/operation											
Construction		×				×	×		×		
Land use/noise/ terrestrial		×	×	×		×	×		×		
Transmission: land		×				×	×		×		
Transmission: EMF		×				×	×		×		
Explosion/accident	×	×	×	×	×	×	×	×	×	×	×
Nuclear accident											
Spills						×					
Decommissioning		×				×	×		×		×
Use of public facilities	×				×				×		×
Socioeconomic	×	×	×	×	×	×	×	×	×	×	×

Source: Ref. [17], later published as Vol. 2 of EMPIRE STATE ELECTRIC ENERGY RESEARCH CORPORATION, New York State Environmental Externalities Cost Study: Report and Computer Model, Oceana Publications, Dobbs Ferry, NY (1995). The table is reproduced from pp. 299, 300 of Vol. 2.

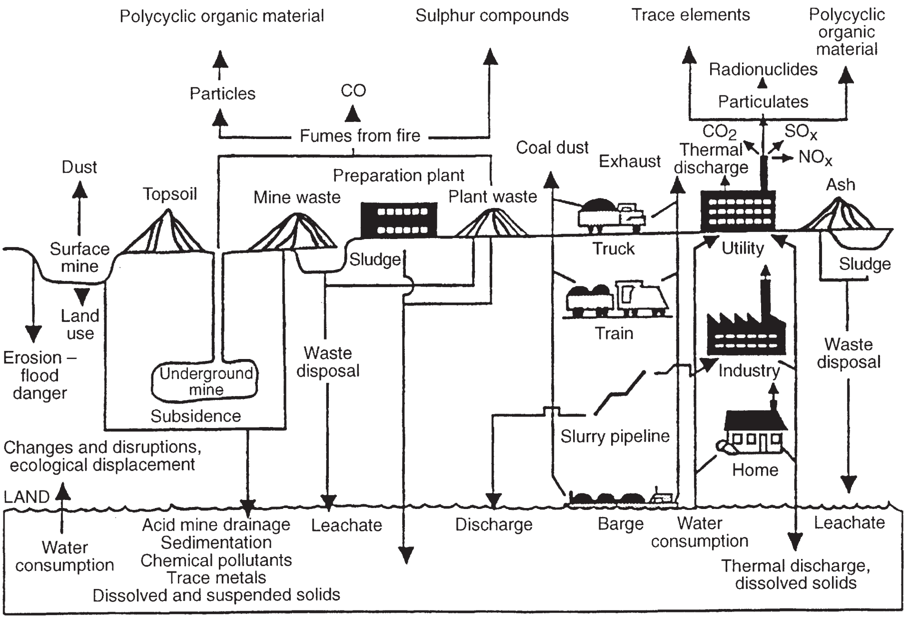

FIG. 3. Illustration of fuel chain concept (adapted from Ref. [8]).

are typically not considered, whereas the impact pathway approach focuses on these and generally does not consider the financial costs of production. In the sense of the present report, this is a restriction of the boundaries of the problem.

Other categories of methods are life cycle assessment, ecological risk analysis and health risk analysis. In all of these, a pathway analysis is undertaken, much like the impact pathway approach. The typical difference between the two types of approach is that ecological and health risk analyses frequently focus on detailed descriptions of the pathway for a particular species or health end point. By contrast, a fuel cycle or fuel chain analysis, which uses an impact pathway approach, focuses on a range of impacts from a particular fuel chain rather than on a single impact. Another frequent difference is that ecological and health risk analyses usually stop short of any economic valuation of the impacts, whereas studies that use the impact pathway approach frequently emphasize the calculation of economic values.

Some studies make a distinction between total energy cycle analysis and fuel chain analysis. The main difference is that total energy cycle analysis considers the impacts of end use technology (e.g. electric vehicles) as well as the fuel cycle. Again, this represents a distinction in the boundaries of the problem between the two approaches.

Finally, it should be made clear that the methods described in this report include techniques commonly used in comparative risk assessment in the nuclear industry, but are more general than these. The conventional definition of risk in the nuclear industry is that it equals the probability or relative frequency of the occurrence of events multiplied by the consequences of the events. This approach is suggested in Section 3.6.4 for severe reactor accidents and for other types of severe accidents, such as major oil spills. For all other pathways, however, the events (e.g. emissions of pollutants from fossil fuelled plants) are assumed to occur with certainty, although their effects may be uncertain for an individual and follow probabilistic criteria.

3.2. DEFINITION OF SCOPE

The first step in undertaking an impact pathway (damage function) study is to determine its scope and the resources available to complete the study. This section briefly describes these basic tasks and the questions associated with the study.

3.2.1. Specification

It is important that analysts who undertake a study of the health and environmental impacts of fuel chains obtain the answers to fundamental questions about the scope of the study. These answers frame the context and nature of the study, make it more relevant to the issues at hand and make it more useful to the ‘customers’ of the study. The analysts must also consider very carefully during the preparation of their report, to whom, when and how the analysis is to be presented.

Table III presents a checklist that can be used to define the scope of a study and to proceed on a certain path for the analysis.

In carrying out any study, it is important to keep in mind what the results are to be used for. Otherwise, one risks calculating impacts that have little to do with the policy or planning decisions to be made. The methodological approach that Section 3 describes is best suited to project- and site-specific situations; for example, if a new power plant is needed, which type should be built and where? There are other, more aggregate, contexts that are considered in energy planning as well, e.g. ‘green accounting’ and major centralized or national policies such as promoting either coal or nuclear energy. The methods described in this report are less suited to these aggregate issues. A range of ‘representative’ sites and technologies would have to be considered for aggregate studies. The results of analysis of these sites and technology options may then be used as inputs to a broader assessment at the national level, possibly to some computable general equilibrium model (as in an ongoing project sponsored by the European Commission (EC)).

TABLE III. CHECKLIST TO ASSESS SCOPE OF STUDY

Question to be addressed	Action required
Nature of energy options	
What is the context of the study?	Define the purpose and specific objectives as explicitly as possible. The analysis and report for the study should contain a concise, specific description of the scope, and of the rationale in defining it Characterize the energy options in general terms
What are the specific options to be compared?	Define the specific options to be considered. Describe the nature of each fuel chain (each stage in a fuel chain has its own life cycle)
What data are needed on each option?	Characterize the energy technology so that the important data to be used in the subsequent analysis are specified. These data include the power plant's capacity, annual generation, emissions and height of stack (if any) Determine whether to use actual or proposed power plants, reference or benchmark plants, or aggregate emissions from a country If the options include a technology that is not yet in operation or commercially available, then it is obviously difficult to characterize its emissions. Estimates would have to be extrapolated from data from experiments, pilot plants or engineering judgement. It is advisable, especially when dealing with future technologies, to do calculations with different sets of assumptions, each set representing high, low or best guess assumptions about the emissions
Customer	
Who is the customer for the study?	Determine who is funding the study, the reviewers, the likely readers and users of the study report, and those most likely to be affected by the results
What are the final results to be used for? What is the desired output from the analysis?	Identify specific ways in which the results will be used. Define appropriate boundaries to delimit the study: —*Time frame:* acute, lifetime or intergenerational. Impacts differ for different fuel chains

TABLE III. (cont.)

Question to be addressed	Action required
	—*Geographical scale:* own country or global. For developed countries, the study should include the global scale; for developing countries, this is optional. Consider too that a low dose to large populations far away may add up to a significant impact —*Externalities:* decide whether externalities for imported fuel are to be considered —*Extent of life cycle and indirect impacts:* review which parts of the life cycle are more important. Do the minimum amount of analysis that gives a large proportion of the total costs
	Decide on specific impact indicators to be estimated
Have uncertainties been considered and important issues highlighted?	For example, consider the issue of whether fine particles are really responsible for health effects at ambient levels, and the associated uncertainty

3.2.2. Resources

After the scope of the study has been determined, it is necessary to take stock of the available resources. These include the budget for the study, staff expertise and the time available to complete the study. This information, together with knowledge of the scope of the study, should be used to decide on an overall study approach.

The methodological approach is multidisciplinary. Thus, a multidisciplinary team should be formed for the study. It will also be helpful to develop contacts with experts in the major fields that the impact pathway approach encompasses. Table IV lists the major types of analysis that an impact pathway study entails, and the types of professional staff that would be suitable for carrying out the study. Corresponding to the last four rows in the first column of the table are the types of professional staff that would be suitable for carrying out comparative assessments as described in Section 4.

In addition to staffing the project team, it is necessary to identify data and model/software needs and their availability (Sections 3.4.2 and 3.4.3). Also, the screening exercise (Section 3.3) may reveal additional resource requirements.

A summary of Section 3.2 is shown in Table V.

TABLE IV. SUMMARY OF STAFF EXPERTISE REQUIRED FOR IMPACT PATHWAY ANALYSIS

Type of analysis or activity	Type of expertise needed
Project management	Someone who is multidisciplinary in his/her thinking and an expert in many, if not all, of the issues involved, with the ability to talk to natural scientists and engineers as well as social scientists
Characterization of fuel chain and technology	Industry experts Engineers
Estimation of changes in pollutant concentrations and other risk factors	Atmospheric transport modellers and atmospheric chemists Aquatic ecologists Computer programmers Nuclear engineers Industry experts Staff members of environmental regulatory agencies
Calculation of expected impacts	Environmental scientists Environmental engineers and analysts Health scientists and epidemiologists
Translation of impacts into economic damages	Economists
Identification of externalities	Economists Planners Policy analysts Geographers Lawyers
Multicriteria analysis	Management scientists Decision analysts
Synthesis	Generalists who have a good grasp of the overall problems and issues, e.g.: Environmental analysts Policy analysts Geographers

TABLE V. SUMMARY OF DEFINITION OF SCOPE

Information input	Background reports, memoranda and papers Scope of work statement, terms of reference or prospectus Discussions with relevant staff and supervisors Discussions with stakeholders
Type of analysis	Reviews and discussions
Output of analysis	Understanding of context of study, stakeholders, primary issues Customer(s) for study; type of results and report Fuel chain options to be considered Type and depth of study Boundaries, time-scale, etc., for study Budgetary and staff resources for study Models available and expertise to apply them

3.3. INITIAL SCREENING ANALYSIS

3.3.1. Fuel chain activities

The scoping described in Section 3.2 defines the fuel chains that the study is to address. As discussed in Section 2, a fuel chain consists of a sequence of activities or production processes. These processes differ between fuel chains. Since the guidance in this report is to enable comparisons to be made, it is important to consider all reasonable fuel chains.

After a general category of fuel chain is selected for analysis, it is necessary to describe its technologies. This description should be in general terms, specifying the source and type of fuel, the nature and location of any fuel refining or storage activities, the mode and route of transporting the fuel to the power plant, and the type and location of the waste disposal activities. The purpose of this part of the analysis is to identify the major stages of the fuel chain, the nature of the activities at each stage and the major discharges from these activities.

It is not necessary to have a highly detailed engineering description of the technology because most of this information would not be used to calculate the results. One main reason is that previous studies have indicated that some types of emission are much more important than others in terms of their impacts on health and the environment. Thus, the study can focus on these more important emissions. The second main reason is that the current state of knowledge is insufficient in certain areas to model or estimate an impact adequately. All that is needed are general descriptions of the fuel chain activities. Examples of this aspect of the analysis are provided in Refs [2–15].

3.3.2. Possible impacts of different fuel chains

After defining fuel chain activities, the next step in the analysis is to survey possible impacts of different fuel chains. The severities of the hazards listed below are not necessarily of the same magnitude or significance, though they generally reflect the more important concerns within each category in the list:

(1) Fossil fuelled power plants
(a) Coal fired power plants

Occupational hazards

- Accidents and illnesses connected with production of materials needed for plant and mine construction;
- Accidents arising from mine construction and operation;
- Occupational pneumoconiosis (black lung disease) and lung cancer;
- Vibration disease;
- Occupational cancer arising from radon exposure;
- Accidents during construction of the power plant;
- Accidents in transportation of coal to the power plant;
- Accidents in operation of the power plant.

Public hazards

- Injuries and mortality connected with accidents in coal transportation;
- Effects of inhalation of pollutants released during production of materials needed for plant and mine construction;
- Effects of inhalation of pollutants from coal combustion released during power plant operation;
- Somatic and genetic effects attributable to radiological impacts of the coal fuel cycle;
- Solid and liquid wastes containing toxic substances.

Environmental impacts

- Loss of land for open pit mining, or mining damage in underground mine areas, including damage to urban infrastructure;
- Pollution of water due to liquid effluents from mines;
- Pollution of water due to solid and liquid wastes from the power plant;
- Loss of forests, crops and animals due to absorption of pollutants from coal combustion released during power plant operation;

- Global warming due to CO_2 released during plant operation, material production and plant construction.

(b) Oil fired power plants

Occupational hazards
- Accidents and illnesses connected with production of materials needed for plant construction, oil field development and transport line construction;
- Drilling accidents;
- Cancer in oil refinery workers arising from exposure to carcinogenic hydrocarbons;
- Accidents during construction of the power plant, oil field development and transport line construction;
- Accidents in transportation of oil to the power plant and oil storage;
- Accidents in operation of the power plant.

Public hazards
- Injuries and mortality connected with accidents in oil transportation;
- Effects of inhalation of pollutants released during production of materials needed for plant construction and oil field development;
- Effects of inhalation of pollutants from oil combustion released during power plant operation;
- Solid and liquid wastes containing toxic substances;
- Fires and explosions of stored oil.

Environmental impacts
- Pollution of water due to liquid effluents from oil transportation and accidents;
- Pollution of water due to solid and liquid wastes from the power plant;
- Loss of forests, crops and animals due to absorption of pollutants from oil combustion released during power plant operation;
- Global warming due to CO_2 released during plant operation, material production and plant construction.

(c) Natural gas fired power plants

Occupational hazards
- Accidents and illnesses connected with production of materials needed for plant construction, gas field development and transport line construction;
- Drilling accidents;
- Accidents during construction of the power plant, gas field development and transport line construction;

- Accidents in transportation of gas to the power plant and gas storage;
- Accidents in operation of the power plant.

Public hazards

- Injuries and mortality connected with accidents in gas transportation;
- Effects of inhalation of pollutants released during production of materials needed for plant construction and gas field development;
- Effects of inhalation of pollutants from gas combustion released during power plant operation;
- Solid and liquid wastes containing toxic substances;
- Fires and explosions of stored gas.

Environmental impacts

- Loss of forests, crops and animals due to absorption of pollutants from gas combustion released during power plant operation;
- Global warming due to CO_2 released during plant operation, material production and plant construction.

(2) Nuclear power plants

Occupational hazards

- Accidents and illnesses connected with production of materials needed for construction of the power plant and associated facilities;
- Accidents arising from uranium mine construction and operation;
- Occupational pneumoconiosis;
- Occupational cancer arising from radon exposure;
- Accidents during construction of the power plant;
- Accidents in transportation of fuel to the power plant;
- Accidents in operation of the power plant;
- Accidents in waste disposal and fuel reprocessing (for a closed fuel cycle);
- Somatic and genetic effects of exposure to radionuclides during power plant operation (including maintenance and accidents), radioactive waste handling and disposal, and fuel reprocessing.

Public hazards

- Effects of inhalation of pollutants released during production of materials needed for plant and uranium mine construction;
- Somatic and genetic effects of routine and accidental exposure to airborne, water-borne and food-chain-borne radionuclides from uranium mining, fuel processing, plant operation and waste management;

- Injuries and mortality connected with non-radiological accidents in material transportation;
- Long term exposure of many generations to very low radiation fields due to long lived radioactive gases released to the atmosphere;
- Non-radioactive releases/impacts from uranium mining.

Environmental impacts

- Loss of land for uranium mining;
- Pollution of water due to liquid effluents from uranium mines;
- Effects of radiation on plants and animals in the case of severe reactor accidents;
- Water heating by waste heat;
- Global warming due to CO_2 released during material production and plant construction.

(3) Hydropower plants

Occupational hazards

- Accidents and illnesses connected with production of materials needed for plant and reservoir construction;
- Accidents during construction of the plant and reservoir.

Public hazards

- Effects of inhalation of pollutants released during production of materials needed for plant and reservoir construction;
- Effects of inhalation of pollutants released during construction of the plant and reservoir;
- Relocation of large populations (e.g. up to 1.2 million people in the case of the Yangtse dam in China);
- Health problems in coastal waters due to growth of vegetation, muddy water and mosquitoes (e.g. in the area of the Aswan dam in Egypt);
- Dam breaks.

Environmental impacts

- Changes of local or regional climate;
- Influence of reservoir on fishing;
- Water management, including positive aspects (e.g. the possibility to control floods);
- Negative influence on neighbouring land, which may become partly dry or partly wet, with significant changes in groundwater levels in the vicinity of the reservoir;

— Sedimentation of dams, leading to the filling up of the area before the dam and accumulation of toxic substances in sediments;[5]

— Global warming due to CO_2 released during material production and plant construction, and methane released from decomposition of waterlogged vegetation;

— Loss of forests, land, crops, plant species, animals and their habitats, and historical sites;

— Displacement of population.

Occupational and public hazards and environmental impacts connected with production of energy necessary for material production and plant construction

(4) Biomass power plants

Occupational hazards

— Accidents and illnesses connected with intensive fuel growing and harvesting;

— Accidents and illnesses connected with fuel processing and handling;

— Accidents and illnesses connected with production of materials needed for plant construction;

— Accidents and illnesses connected with fuel transportation;

— Accidents and illnesses connected with fuel storage (hazards of self-ignition, biological life development);

— Accidents and illnesses connected with plant operation;

— Accidents and illnesses connected with waste handling.

Public hazards

— Effects of inhalation of pollutants released during plant construction;

— Effects of inhalation of pollutants released during plant operation (total suspended particulate matter, polycyclic aromatic hydrocarbons, formaldehyde);

— Effects of exposure to pathogens;

— Effects of odours from stored fuel;

— Hazards connected with fuel transportation.

Environmental impacts

— Effects of diesel exhaust from harvesting equipment;

— Occupancy of land by a monoculture and associated problems with biodiversity;

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[5] The sedimentation should also be considered in determining the lifetime of the plant, which can have a significant influence on its economics.

- Global warming due to CO_2 released during material production and plant construction.[6]

Occupational and public hazards and environmental impacts connected with production of energy necessary for material production and plant construction

(5) Solar power plants[7]

Occupational hazards

- Hazards connected with production of materials needed for photovoltaic cells (aluminium, silicon, steel);
- Hazards connected with construction and maintenance of plant and energy backup or storage systems;
- Hazards connected with material transportation;
- Effects of routine and accidental exposure to toxic chemicals used in device fabrication.

Public hazards

- Effects of inhalation of pollutants emitted during material production;
- Hazards connected with material transportation;
- Health effects of discharges from energy backup or storage systems;
- Effects of routine and accidental exposure to toxic chemicals released in device fabrication.

Environmental impacts

- Occupancy of land;
- Effects of discharges from energy backup or storage systems;
- Global warming due to CO_2 released during material production and plant construction.

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[6] In a balanced system, the CO_2 releases during plant operation are equalized by CO_2 absorption in plants during fuel growing.

[7] Solar power plants can be based on thermal processes (concentrator farms, feeding of energy to heat exchangers and turbine plants, solar towers with mirrors directing energy to the central receptor, or a Stirling engine placed at the focus of a large mirror, which provides high efficiency but is not yet economical) or on photovoltaic cells. The latter variant seems to have better chances for development, so the impacts listed are based on static photovoltaic technology.

Occupational and public hazards and environmental impacts connected with production of energy necessary for material production and plant construction

Material constraints (limited supply of silver)

(6) Wind power plants

Occupational hazards

- Accidents and illnesses connected with production and transportation of materials needed for windmill construction;
- Accidents and illnesses connected with construction of the power plant;
- Accidents and illnesses connected with maintenance of the power plant;
- Hazards connected with energy backup or storage systems (batteries or pumped storage).

Public hazards

- Effects of inhalation of pollutants released during production of materials needed for plant construction;
- Injuries and mortality connected with accidents in material transportation;
- Hazards connected with energy backup or storage systems.

Environmental impacts

- Global warming due to CO_2 released during material production and plant construction;
- Occupancy of land;
- Effects connected with energy backup or storage systems.

Occupational and public hazards and environmental impacts connected with production of energy necessary for material production and plant construction

Other impacts

- Noise;
- TV interference;
- Hazards to birds;
- Stroboscopic effects on human and animal sight.

(7) Transmission lines

Occupational hazards

- Accidents during construction and maintenance of the lines.

Public hazards

- Breakdown of the lines;
- Health effects of electric and electromagnetic fields.[8]

Environmental impacts

- Occupancy of land.

Other impacts

- Hazards to birds.

3.3.3. Identification of priority impact pathways

After possible impacts have been surveyed, the next step is to decide which impact pathways are more important. There are too many stages in a typical fuel chain, and too many emissions and impacts for a study to be able to consider all of them in detail. Furthermore, limitations in knowledge pose significant constraints on the number of impact pathways that can be analysed. Thus, it is necessary to identify the impact pathways to which the study will give priority.

To assist in making this assessment, some studies have suggested that an ‘accounting framework’ be used. This accounting framework helps to organize the thinking about the sequence of physical, chemical and biological processes that take place when the discharges from a fuel chain activity affect the state of the environment or human health. The technologies or activities are characterized by their residual emissions. Data for these characterizations are extracted from existing literature. Once emissions and other residuals are characterized for each stage of the fuel chain, the next part of the pathway is the mapping of emissions into pollutant concentrations. Then the concentrations are linked to physical impacts. Ecological and health impacts are discussed more fully in Ref. [8] (sections 3 and 4, respectively). The next mapping in the accounting framework represents the translation of physical impacts into marginal damages, i.e. damages resulting from an incremental increase in emissions. Underlying the entries in the accounting matrix are the valuation functions that match physical impacts and monetary values. References [3, 9, 10, 17] contain detailed discussions of economic valuation in the context of the US and EC projects.

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[8] There have been over a hundred epidemiological studies of possible effects of electromagnetic fields on health. Many of them claim a positive, statistically significant association but none goes so far as to attribute causality. None of the official or quasi-official reports concludes that there is an effect which must be guarded against. Nevertheless, considerable public concern remains, and further studies are under way.

A screening process is used to select the priority emissions/impacts categories that are the most relevant to the fuel chain options under consideration. This screening should be based on specific criteria such as those listed below:

(a) The anticipated or possible importance of a discharge, as gauged by the expected size of the damage or externality; for example, discharges would generally not be selected for study if they were judged to have a relatively small impact compared with other impact pathways, if their effects were highly site specific and required additional collection of primary data, and if the impacts were primarily to the property of the operator of the power plant.
(b) The availability of quantitative information about the impact pathway, specifically dose–response functions (but this criterion should not be used to eliminate from consideration contentious but potentially important issues).
(c) The desire for comparison of impacts common to different fuel chains, even if they are unimportant in some fuel chains.
(d) The desire to have a sample of impacts that span the major stages of the fuel chain (the stages will vary because of intrinsic differences among fuel chains).

To identify the priority impact pathways, analysts should take note of the impacts that previous studies have identified. The priority impact pathways that this screening analysis selects are then analysed using the impact pathway approach.

It is advisable that the screening be done in a formal way. The New York State study [16–20] offers an excellent example of a structured screening approach. It is suggested that screening criteria similar to those used in Ref. [16] or Ref. [10], section 4, be defined, and that impact pathways be evaluated on the basis of these criteria. The assessments are best summarized in the form of a matrix, with the criteria as the columns and the rows representing the impact pathways, organized by stage of fuel chain and type of pollutant. It is important to state why a particular stage of the fuel chain, or impact, is omitted from further, detailed consideration.

Studies should not duplicate the screening exercises that have been done in previous studies. Rather, the screening should take advantage of these previous efforts. Thus, the matrix that summarizes the screening can make reference to the judgements of screening done in previous studies by citing those studies and the specific pages in the reports of those studies.

The screening sets the stage for the more detailed pathway analysis to follow, thereby establishing the impacts to be examined in greater detail. The screening analysis may, in some cases, determine that some of the stages of the fuel chain are relatively insignificant in terms of their overall health and environmental impacts. These stages can then be omitted from subsequent, more detailed analysis. The screening also identifies impacts that are less important and impacts that, although

TABLE VI. SUMMARY OF SCREENING ANALYSIS

Information input	Scope of study, including fuel chains to be considered Previous studies that estimate impact indicators Other specific studies, for additional background information Information about the fuel chains and technologies
Type of analysis	Review and assessment of possible impacts Selection of most important impact pathways (assessment summarized in matrix)
Output of analysis	Priority impact pathways Impact pathways that are not considered further

sizeable, are not externalities (and which thus, depending on the scope of the study, need not be addressed further).

The impacts that are the most important will vary, depending on the type of fuel chain and on the regional environment. Local ecological impacts and aesthetic impacts are usually more important in renewable energy projects (which have a low energy density) such as wind, geothermal and biomass power projects and small hydropower developments, compared with nuclear and fossil fuelled power projects. Likewise, occupational impacts (e.g. wood harvesting for biomass and production of materials for power plant construction) may be relatively large for these low energy density options.

A summary of Section 3.3 is shown in Table VI.

3.4. CHARACTERIZATION OF FUEL CHAIN AND TECHNOLOGY

3.4.1. Technology and scale of fuel chain activities

This section discusses important issues that should be considered in defining the fuel chain activity, which is the first main step of the impact pathway approach:

Fuel chain activity → Source term → Changes in concentration → Impact

This first step involves engineering analysis to identify and describe the activities and engineering processes in various stages of the fuel chain. Technologies and power plant designs are specified and the emissions from each stage are estimated. The amount of information that should be collected will depend on the type and purpose of the study. In general, enough information should be provided so that readers of the final report will have basic information about the power plant; but detailed engineering descriptions and data that will not be used for any impact indicator are generally unnecessary.

The first type of information to collect is for calculating the annual generation (an example of this simple calculation is given in appendix A of Ref. [10]). The power generated depends on the size of the plant, its efficiency in converting fuel to electrical power, the heat content or potential energy in the fuel or source, and the average proportion of time that the plant operates during a year. The quantity of power generated is used to ‘standardize’ the magnitude of the impacts. This standardization facilitates comparisons of impacts of different fuel chains, each with its own different size of power plant. That is, impacts are measured relative to the amount of power generated, i.e. on a per kW(e)·h basis. The total annual damage can be thought of as the numerator and the total annual generation as the denominator in the impact indicator. These data should be compiled for the specific options being considered. ‘Generic’ data can be used if a specific option has not been identified. However, the data should be reviewed to ensure that they are appropriate for the options under consideration.

The second type of information is about the scale of the production processes throughout the fuel chain. For example, the size and efficiency of a coal fired power plant determine the amounts of coal mined and transported to meet its needs. These amounts in turn affect the likelihood of occupational injury and injury to the public. They also determine the size of disturbances to the environment, road damage, etc. If the sources of the fuel or other upstream activities have yet to be determined, then the only recourse is to use some generic data from other sources. However, analysts should use engineering judgement to modify these data, if appropriate, and state the basis for the modifications.

The third type of information is about the kind and efficiency of pollution abatement equipment and other equipment that reduce the discharges or other residual effects of the production process. This information is used in the second part of this step of the analysis, which sets the magnitude of the emissions (Section 3.4.2). As mentioned above, if a specific power plant is not being considered, then it will be necessary to compile data for some generic power plant. It is important, however, that the data are relevant to the power plant being considered. For example, data on emissions from ‘old’ coal fired power plants should not be used if the option under consideration is a new plant with efficient pollution abatement equipment. Table VII in Section 3.4.2 lists some of the key data that should be collected.

Thus, this part of the analysis provides three types of information:

(a) Annual generation (e.g. in kilowatt-hours or megawatt-hours),
(b) Magnitude of other activities in the fuel chain (e.g. tonnes of coal mined),
(c) Annual or expected discharges and other residual effects from production (e.g. in tonnes).

Power plants are not only of different sizes but may also serve different purposes. Direct comparisons should be avoided between peak load and baseload plants. For example, if a natural gas fired power plant is to be used for baseload operation, as is the case in some countries and is proposed for several other countries, it should be compared with a baseload coal fired power plant. The natural gas plant should then have the design and operating characteristics of a baseload plant and not those of a peak load plant. For instance, it could be a combined cycle plant, with high investment costs but high efficiency.

Some power sources are intermittent and uncontrollable in that they do not provide continuous electrical power. This intermittent nature is characteristic of certain renewable energy technologies such as solar and wind power. They require a backup source of power and/or storage devices to store power for later use. Both solar and wind power plants are to some degree predictable, but they are certainly uncontrollable. For example, in contrast to conventional power plants, where shutdown periods can be planned so as to avoid disturbances in the power network, all solar power plants will stop producing energy during the night.

When these sources are part of a large network (electricity grid), the solar and wind energy sources can be integrated with negligible additional costs up to some level, depending on the power system configuration and load distribution. When the fraction of energy generated by, for example, solar energy sources increases, the backup function of the network becomes more pronounced and the costs increase. The solutions envisaged for the future, such as pumped energy storage and conversion to hydrogen, are also associated with large investment costs and losses of efficiency due to energy conversion within the support system. These circumstances should be taken into account when estimating the impacts and risks of the whole system.

In the case of stand-alone units the necessity of backup systems and/or storage devices becomes evident.

Analysis of energy technology options should explicitly account for the expected impacts associated with these supplementary facilities, and should add these impacts to those estimated for the power plant itself, if the requirements for different energy options are to be comparable.

3.4.2. Type and magnitude of emissions and other residual burdens

The next part of this step in the analysis is to determine the type and magnitude of the emissions and other residual burdens. This section discusses important considerations related to the part of the impact pathway approach highlighted below:

Fuel chain activity → Source term → Changes in concentration → Impact

Discharges from fuel chain activities can be thought of as occurring either frequently, on a more or less continuous basis, or rarely if at all. Airborne pollutants from operating fossil fuelled plants fall under the first category, whereas releases of radionuclides in the event of a severe nuclear reactor accident would fall under the second category. For the first category of discharges, emissions are typically measured on an annual basis (e.g. tonnes/year). Estimates of these discharges are obtained from historical data on actual emissions.

The second category of discharges comprises those from very low probability events. Generally, reliable estimates of future occurrences cannot be made on the basis of historical data because of an insufficient number of events. Thus, delineation of these rare events is usually done using combined event tree and fault tree analysis. In nuclear applications the source terms resulting from this approach are then embedded into computer codes, such as COSYMA [51] and MACCS [52], which allow probabilistic analysis of the associated consequences. The remainder of this section focuses on the first type of emissions, those that occur on essentially a continuous basis throughout the year. The second type of emissions is discussed in Section 3.5.5.

For the first category of discharges, information should be compiled, at a minimum, on the following airborne pollutants:

- SO_2;
- NO_x;
- Particulate matter;
- CO_2 and other greenhouse gases, including CH_4;
- Radionuclides.

These pollutants are from fossil fuel combustion. The data on these pollutants are important because there are many models and considerable scientific literature that permit detailed analysis of the dispersion and impacts of these pollutants. The scientific literature on CO_2 reflects considerable uncertainty about the magnitude of the impacts from global climate change. The corresponding impact indicator may simply have to be the emissions of CO_2, rather than estimates of particular impacts or economic damages.

Data may also be compiled for other discharges such as:

- Lead
- Mercury
- Toxic chemicals.

Impact pathway models have not been as well developed for these chemicals as for those in the previous list. Thus, impact indicators associated with the discharges listed above may simply be the magnitude of the discharge itself, rather than estimates of the health and environmental impacts, although the uncertainty associated with this limited approach must always be kept in mind.

For fuel chains that do not involve fuel combustion to generate electrical power, Refs [6, 7, 13, 15, 17] list many of the residual effects that previous studies have considered. Table II [17] (Section 3.1.4) presents a taxonomy of the different types of discharges and other residual effects that stem from each type of fuel chain. For the purposes of their own studies, analysts may wish to develop more detailed versions of this table that have a breakdown of the different stages of the fuel chains: plant construction, including transport activity; fuel extraction and preparation; fuel transport; generation; and waste disposal and waste handling (Fig. 1). Analysts may also find that one of the many flow charts available is useful here (e.g. Fig. 1 or Refs [3, 10, 16]).

Data on emissions and other discharges are obtained from one or more of three sources:

(a) Records of actual emissions if the power plant, or one similar to that being assessed, already exists. It is preferable to use these sources of data if possible.

(b) Engineering calculations and expert judgement based on the design specifications and expected efficiency of the power plant and its pollution abatement equipment. These estimates should be validated by checking ‘real’ data (e.g. by contacting a company or industry representative) and by comparing them with previously published estimates.

(c) Previously compiled records on other, or on generic, power plants. This option is generally the least attractive but sometimes the only one available. Several databases contain data on emissions from power plants. Some of these databases are listed in Table I. Some databases also contain data on other fuel chain activities.

Table VII lists some of the key data that should be compiled. Table I lists some sources of estimates for these data, if primary data are unavailable or cannot be calculated. Another source of data is Ref. [53]. References [2–21] provide extensive lists and other information on the most relevant source terms for each of the fuel chains.

There are secondary or indirect discharges that result in impacts. Examples of these discharges are: air pollution from the manufacture of copper, concrete and steel used to construct power plants and dams; disposal of toxic chemicals that are used in the manufacture of photovoltaic cells; and diesel exhaust from harvesting equipment for biomass plantations.

There are only a few studies to date that have quantified the magnitudes of these types of discharges. Because of the large amount of construction materials used, secondary discharges from their production have a particular importance for hydropower and other renewable resources. In non-fossil fuel chains, secondary emissions contribute the major share of the total emissions.

TABLE VII. TYPES OF DATA THAT SHOULD BE COLLECTED ON FUEL CHAIN ACTIVITIES

Stage of fuel chain	General type of data
Fuel production	Nature and amounts of fuel produced and discharges and other residual effects (e.g. biomass feedstocks and amount of pesticides used) (e.g. tonnes per year)
Fuel transportation	Mode and route of transportation and average accident rate in this mode Capacity of carriers (e.g. 10 tonne trucks)
Electricity generation	Type of power plant (e.g. coal fired, pulverized fuel) Capacity of power plant (MW(e)) Efficiency (%) and annual generation (MW(e)·h) of power plant Nature and amounts of discharges and other residual effects (e.g. SO_2, NO_x, particulate matter, CO_2) (grams per second or tonnes per year) Pollution abatement equipment and other safeguards (percentage of pollutant removed compared with unabated emissions) Operational lifetime of power plant (years)
Waste disposal and decommissioning	Nature of decommissioning and residual effects Nature, amount, location and route for waste disposal

For the higher energy density sources, estimates of CO_2, particulate matter and other air pollutants arising from the production of materials used in constructing power plants indicate that they are between one and two orders of magnitude less than the emissions from current coal fired power plants. With advanced technologies, the emissions from coal fired power plants may be only ten times greater than secondary emissions. This estimate is on an annualized basis in that the emissions associated with the construction of a power plant occur once, whereas the emissions from a power plant are over the duration of its operation (e.g. 40 years). Thus, when the secondary emissions from the construction of a coal fired plant are expressed on the basis of the total number of kilowatt-hours (electric) generated by the power plant over its lifetime, the CO_2 emissions from construction and the materials used in construction are relatively low compared with annual emissions of CO_2 from the operation of a coal fired power plant. However, the impacts from construction take place during the current time period, whereas impacts from emissions take place in the future and should be discounted (though there is considerable debate about discounting intergenerational impacts) as discussed in Section 5.2.4.

In summary, there is evidence that secondary effects are relatively insignificant for fossil fuel chains [10, 15], but that they are very significant, relative to other sources within the fuel chain, for non-fossil fuel chains. Analysts should check whether there are any special conditions that may change this generalization in the specific context that is being evaluated. Further discussion on this subject is provided in Section 5.1.1.

3.4.3. Data on receptors and the environment

In addition to data on the fuel chain, the technology for generating electrical power, and the discharges and other residual effects of generating electrical power, data are required on the receptors and on other environmental conditions. Receptors are the entities that are subject to exposure to one or more pollutants and that change as a result of this exposure. These changes are the impacts. The other environmental conditions on which data are needed are factors that affect the magnitude of the dispersion and concentration of pollutants. Table VIII lists receptors and other environmental conditions for which data should be compiled. This list is not exhaustive but indicates many of the more important data elements.

A summary of Section 3.4 is presented in Table IX.

3.5. ESTIMATION OF CHANGES IN POLLUTANT CONCENTRATIONS AND OTHER RISK FACTORS

This section describes the type of analysis required to estimate changes in pollutant concentrations. That is, this section focuses on the part of the impact pathway approach highlighted below:

Fuel chain activity → **Source term → Changes in concentration** → Impact

This step of the method estimates changes in the conditions that affect the likelihood of adverse impacts. Examples of these conditions include concentrations of pollutants, erosion and accidents. The source terms of these conditions are pollutant emissions, changes in land use (e.g. for biomass) and power plant operations, respectively. Computer codes or other calculations are used to model the

TABLE VIII. TYPES OF DATA NEEDED ON RECEPTORS AND ON OTHER ENVIRONMENTAL CONDITIONS

General type of data	Variable for which data are needed
Receptor	
Population	Number of people in areas around the power plant(s). Data should be for: regular rectangular grid; radial segments (defined by distance and direction from power plant); or census areas It is useful to have an age breakdown if possible, especially for the young and the elderly It may be useful to have a socioeconomic breakdown for purposes of considering equity concerns by estimating impacts on different socioeconomic groups Population estimates at other sites of fuel chain activities (e.g. mine sites if there is any off-site dispersion, and transportation routes if there is the possibility of accidents and dispersion of contaminants)
Anthropological factors	Items of great cultural or spiritual significance (e.g. archaeological sites)
Agricultural land use	Area and yield, by type of crop Livestock population, by type of livestock
Infrastructure	Number of buildings (population estimate can be used as a surrogate) Structures of great historical or other significance (e.g. statues) Length of route used to transport fuel
Fish and other aquatic populations	Fish: general type of species (some species may be endangered) Usually included in the data sets of oil spill models
Other flora and fauna	Types of flora and fauna, especially threatened or endangered species
Forest	Type and area of forests
Existing land use	If new construction is to take place in a sensitive area, data are required on the type of land use being lost. This will be especially important for hydropower systems and other land intensive uses, such as wind farms

TABLE VIII. (cont.)

General type of data	Variable for which data are needed
Wilderness	Information on whether the area affected has great wilderness and/or scenic value. Positive environmental factors, such as flood control for a hydropower project or a cooling pond as a recreational lake, might be included
Other conditions	
Topography	Elevation of land near power plant (used in some air dispersion models). Model documentation should be checked for specific input requirements
Meteorology	Average wind speed and direction (used in air dispersion models). Model documentation should be checked for specific input requirements
	Hourly wind speed and direction (used in some ozone models). Model documentation should be checked for specific input requirements
Ambient baseline atmospheric conditions	Concentrations of pollutants, such as ozone, chemical species involved in ozone formation (e.g. volatile organic compounds) and particulate matter
River conditions	For dispersion modelling: flow rate of water and sediments, and transfer factors for water to sediment and water to fish for each section of the river. Model documentation should be checked for specific input requirements
Employment	Unemployment relative to national full employment rate
	Types of industrial sectors in the region.

dispersion of oil spills and the release and dispersion of radioactive materials, or to estimate the change in soil erosion or in accident rates. The results of this stage of the analysis are estimates of changes in the concentrations of pollutants or, more generally, in the conditions that affect the probability of adverse impacts.

3.5.1. Important considerations

Of primary importance are the changes in concentrations that result from a fuel chain. Thus, it is important to account for both the background or currently existing concentrations and the incremental increase relative to this background.

TABLE IX. SUMMARY OF CHARACTERIZATION OF FUEL CHAIN AND TECHNOLOGY

Information input	General description of power plant technology and fuel chain (e.g. source of fuel and transportation routes) Data from fuel chain emissions databases, from companies or engineering reports on the specific power plant(s) under consideration, and from population censuses and environmental databases
Type of analysis	Review of data on emissions and other discharges (sources of data are existing databases) Compilation of data for the power plant(s) under consideration (data specific to the plants under consideration) Engineering analysis to 'design', or to check the design of, the power plant(s) (e.g. stack height, exit velocity of pollutants from stack, efficiency of pollution abatement equipment) Compilation of data on receptors and other environmental conditions (e.g. population distribution, ecosystems exposed)
Output of analysis	Annual generation of electrical power from the power plant(s) Amount of activity (e.g. person-years) as a measure of exposure to occupational risk Quantity and location of discharges of pollutants from the major fuel chain activities Data on receptors and other environmental conditions (e.g. population distribution and ecosystems exposed)

Changes in pollutant concentrations and other changes can be characterized by their time frame and geographical scope:

(a) The time frame can be short term (in the same year), intermediate term (within the lifetime of an individual) or long term (intergenerational).
(b) The geographical scope can be local (sometimes arbitrarily set to be 50 or 80 km, or the distance to some local community or county), regional (sometimes set to be 1000 or 1600 km, or the distance to some political unit such as a country) or global.

These classifications are relevant in that they pertain to impacts, which can be categorized in an analogous way (Section 3.6.10). Thus, when estimating changes in concentrations of pollutants, analysts should be aware of the form in which the data are needed to estimate the impacts, and of the desired time frame and geographical scope.

3.5.2. Changes in concentrations of primary airborne pollutants

The analysis of changes in the concentrations of atmospheric pollutants usually involves computer modelling. A model is used to compute the changes in concentrations at different locations. The estimates of these changes are then ‘overlaid’ with data on the population distribution (as summarized in Section 3.4.3) to estimate the impact on these receptors (Section 3.6).

Atmospheric transport models are used to estimate concentrations of pollutants in the air. Primary pollutants are classified as those that do not undergo chemical transformation, or physical aggregation, between the time of discharge from the fuel chain activity and the time of inhalation or ingestion by the receptor. Gaussian plume or Lagrangian models are used for primary pollutants, such as particulate matter, NO_2, SO_2 and air toxics (e.g. arsenic, chromium and dioxin).

According to Gaussian dispersion models, the concentration of a pollutant is described by the product of two empirical Gaussian distributions, one for vertical spread and one for horizontal spread perpendicular to the prevailing wind direction. The plume width parameters are based on empirical correlations and take into account relevant meteorological conditions, which are inputs into the model. The model requires data on the source terms of the pollutants. These source terms are the parameters affecting the rate of discharge and dispersion of pollutants. These data include the height of the stack emitting the pollutant, as well as the exit rate and velocity of the pollutant. Gaussian models are usually reliable for short distances (up to 50–80 km) and for radionuclide emissions where measurement of local population dose is sufficient to assess the impact on the regional population. Examples of this type of modelling are given in Refs [2–21].

For areas with complex topography, Gaussian models may not be appropriate and therefore other models, such as Lagrangian models, must be used. For regional modelling, most analysts prefer Eulerian grid or Lagrangian trajectory models. Examples are the Harwell Trajectory Model (HTM) [2, 4] and models used in the European Monitoring and Evaluation Programme (EMEP) [54]. These models correctly track air masses from place to place while taking into account conservation of mass.

It is now well recognized that pollutant concentrations should be modelled over a long range of 1000 km or more, since pollutants are transported over such distances and thus have impacts on populations and the environment over this range. Another reason is that long range modelling accounts for chemical transformations that take place.

3.5.3. Radionuclides

Radionuclides are a special case of primary airborne pollutants that have received special attention. Gaussian plume dispersion models are used for modelling the distribution of atmospheric releases of radionuclides. Wind rose data, developed from past measurements of the meteorological conditions at each site, represent the average annual conditions. This methodology is usually used for both local and regional assessments. The dispersion of radionuclides is modelled in standard models. References [6, 15, 21] provide additional discussion.

Recent studies point out that emissions from coal fired power plants include radionuclides. One study has suggested that the impacts of these emissions are insignificant [10] compared with those of particulates. Nonetheless, radionuclide emissions should be estimated and taken into account in assessments of coal based fuel chains. This will facilitate consistent comparison of coal based and nuclear fuel chains.

3.5.4. Secondary airborne pollutants

Many pollutants are transformed into secondary pollutants by chemical reactions in the atmosphere. Examples are the reactions that create acid rain and ammonium sulphate particulates from SO_2, and ozone from NO_x in the presence of volatile organic compounds and sunlight. Complex models are needed to address these transformations.

Sulphates and ozone generally turn out to be very significant factors that result in major impacts compared with other causes [2, 10, 55–57]. Models that can be used to estimate sulphate and nitrate concentrations include:

- Harwell Trajectory Model (HTM) for regional transport and chemistry of sulphur and nitrogen emissions [58, 59];
- Windrose Trajectory Model (similar to HTM), developed by the Institut für Energiewirtschaft und rationelle Energieanwendung (IER) at the University of Stuttgart;
- EMEP transfer matrix for acid deposition [54];
- Sector average Limited Mixing Mesoscale Model (SLIM3) [60].

Models that can be used to estimate ozone concentrations include:

- Ozone Isopleth Plotting Mechanism (OZIPM-4) [61];
- Mapping Area-wide Predictions of Ozone (MAP-O_3), developed by Horizon Environmental of Knoxville, Tennessee [62];

— Karlsruhe Atmospheric Mesoscale Model (KAMM), developed by the Institut für Meteorologie und Klimaforschung at the University of Karlsruhe.

Ozone formation is a highly non-linear process. Thus, simple approximations, such as those based on emissions of NO_x, may result in inaccurate estimates. Ozone levels may actually be lower, in some areas, as a result of NO_x emissions [9]. More detailed ozone models, such as the Urban Airshed Model (UAM) and the Reactive Plume Model (RPM), tend to require too much data for most studies. On the other hand, simpler models such as OZIPM-4 tend to lack the spatial detail that is useful in estimating areas of ozone scavenging (decreases in ozone levels) and bulges (increases in ozone levels). The MAP-O_3 model appears to offer a reasonable compromise, but is not as thoroughly tested as the other, previously mentioned ozone models. More information on ozone modelling is provided in Refs [4, 9, 10, 17, 63, 64].

3.5.5. Accidents as a source of impacts

In this section, accidents that take place during the course of fuel cycle activities are discussed as a source of injuries (see also Section 3.6.4). For the purpose of analysis, accidents take one of two forms differing in terms of relative frequency and magnitude of impact. One type of accident, although a rare event, still occurs frequently enough that there are empirical data on past events each year. Examples of this type of accident are construction accidents and rail transportation accidents. When these accidents occur, their impact is usually limited to a small area and a small number of people. Most oil spills also fall under this category — many oil spills occur each year but they are relatively small.

The other type of accident has an extremely low probability. In fact, such an accident may occur only once every few years, or possibly has not occurred at all to date. Were such an accident to occur, however, its effects could be extensive and catastrophic. Examples of accidents of this type are a severe nuclear reactor accident, a dam rupture and a gas explosion.

The analysis of the first type of accident, the more common type, is handled in a relatively straightforward manner. The expected number and severity of accidents that would result from a particular fuel chain activity are calculated on the basis of historical average rates (e.g. accidents per megawatt-hour generated), compared with rates at historical levels of activities. Historical rates provide reasonable estimates of future rates, assuming that past technologies, maintenance practices and regulations are good indicators of those in the future.

The second type of accident is more complicated to analyse. There are two perspectives on accidents of this type. One perspective is provided by conventional engineering analysis based on PSA. The probability of failure of a production system that would result in a severe accident is calculated by estimating the probabilities of the individual components and parts of the system failing. These probabilities are estimated from engineering studies, experiments and data on historical performance, as well as professional judgement. The magnitude of these probabilities is very small (e.g. one in a million), so that historical data are not of much use here. The other perspective relies on public perceptions of the likelihood (and severity) of these accidents. Both perspectives are discussed further in Sections 3.6.4, 3.6.5 and 5.

3.5.6. Aquatic dispersion models [65]

The aquatic environment can be divided into a number of media subjected to different regimes, each requiring a different kind of model:

- Surface waters;
- Seas, lakes and reservoirs;
- Estuaries;
- Rivers and canals;
- Surface runoff of rainwater;
- Stationary subsurface waters;
- Flowing subsurface waters.

Except for the simplest of water bodies, modelling of water quality is sufficiently complex that it must be computerized. Many models are available as general purpose computer software packages that can be configured by users for specific bodies of water. A few simple screening type models are available that can estimate maximum allowable loadings of important conservative and non-conservative pollutants, but they cannot estimate concentrations as a function of source strength.

Models of surface water contamination are either steady state or time dependent. They vary in complexity, containing two or three dimensions, with or without convection, and with or without sinks. The simplest models are no more than solutions to simple equations that use mixing ratios (possibly time dependent) and some removal constants. These are usually sufficient only for routine effluents, and can lead to gross estimation errors even in simple cases.

Unlike atmospheric dispersion models, many water quality models are not readily adjustable to conditions different from those for which they were designed. They tend to be highly site specific. Thus, accommodating site specific conditions may require gross revisions of existing models or use of models specifically designed to be general purpose and easily configured by users.

Relatively simple, straightforward models are available for estimating concentrations in rivers and streams. More complex models are needed for lakes, reservoirs and estuaries, because they are readily stratified and large enough to support complex patterns of flow. Subsurface models are simple in concept, but complicated in execution because of the potential complexity of the subsurface structures.

3.5.6.1. River models

Rivers are modelled as linked segments between nodes, where there are important changes, such as a large discharge, a large intake, the entry of a tributary or a large change in the physical characteristics of the river. Within a segment all conditions are assumed constant except for the flow controlled time of transit to the next downstream node. Non-conservative substances, such as decomposing organics (and the associated oxygen uptake), pathogens, radionuclides with short half-lives, and substances with high rates of deposition, biological accumulation or chemical reaction, are estimated as a function of time while in each segment. Conservative substances accumulate between sources. Some river pollution problems for which maximum concentration is of special concern (such as heat) are modelled as plumes for short and possibly also long distances downstream of the discharge point.

Organic and nutrient loading of rivers is particularly important. A broad range of helpful equations and models is available to assist in determining the self-purification capacity of a river and the maximum organic loading that can be accommodated while maintaining dissolved oxygen levels at specified minimum levels.

3.5.6.2. Lake models

Lakes are generally classified as oligotrophic (low in nutrients, always oxygenated) or eutrophic (high in nutrients, can become anoxic). Oligotrophic lakes therefore do not support abundant growth of plants. Within limits, these lakes can absorb exogenous nutrients and oxidize organic material without damage.

Eutrophic lakes support abundant growth of algae and other aquatic organisms. Dead plants and animals sink to the lower levels of these lakes, where decomposition by microorganisms depletes or eliminates oxygen, with associated killing of oxygen dependent species. Eutrophic lakes cannot absorb large quantities of exogenous nutrients and organic materials without damage.

Oligotrophic lakes are usually phosphate controlled. Vollenweider [66] developed a simple equation that can be used to estimate the loading of nutrient phosphates that can be added to an oligotrophic lake without reaching a critical level: eutrophication can be expected when phosphorous loading reaches two to three times the critical level.

The regime of water flows in lakes can be very complicated, with some parts of the water stagnating while other parts are flowing like rivers without mixing with the surrounding waters. For this reason simple calculations assuming complete mixing and using materials balance equations may be completely misleading. In addition, the water in the lake is strongly stratified. In large and deep lakes this stratification is completely disturbed according to the season.

Extreme prudence has to be exerted if pollutants or heat loads are to be discharged into lakes.

3.5.6.3. Modelling of transport in subsurface aquifers

Contamination of subsurface aquifers is modelled in two phases:

- Vertical transport through the unsaturated zone
- Plume-like spreading and transport through the aquifer.

Vertical transport of pollutants through the unsaturated zone above an aquifer is a function of the physical and chemical characteristics of the pollutant and the percolation characteristics of the soil. Many organic pollutants are relatively non-polar and hydrophobic, so they tend to sorb into soils and migrate more slowly than polar pollutants. Inorganic chemicals can precipitate out. Some low density organics can even float. Soils differ greatly in their physical and chemical characteristics and their interactions with specific pollutants.

Once in the aquifer, pollutants form plumes by diffusion and transport in gravity driven water flow. Again, the rates of movement are controlled by the physical and chemical characteristics of the pollutant and the hydrogeology of the aquifer. Modelling movement in sand is simple; modelling movement in fractured rock or solution cavities is far more complex.

These characteristics are incorporated into models by combining a groundwater flow equation and a chemical mass transport equation. There are separate models for unsaturated and saturated zones, but they are often linked in comprehensive computer codes.

Groundwater flow modelling requires powerful computer models and the availability of a great number of data. Hydrogeological data may be obtained from cores taken in boring and from classical hydraulic tests (pumping, water injection, water table level measurements, etc.). These tests should if possible be complemented with more specialized tests such as water sample chemical analyses, temperature measurements, use of radioactive tracers, flow measurements and isotopic sampling (e.g. for ^{18}O content).

The geophysical and hydrological characteristics that must be modelled commonly vary by large amounts over short distances. Also, because sampling requires expensive drilling programmes, data are often sparse.

Oil refineries placed onshore, sometimes in large industrial areas, are the cause of environmental impacts both in normal operation and in accident conditions. The impurities in effluent water from refineries are of the following kinds: those in solution (e.g. soluble salts and organic compounds); and insoluble material (e.g. oil fractions of higher molecular weight and suspended solids).

Problems with data quality, together with the long time spans involved in groundwater movements, have hindered verification of models for groundwater transport. Most are not fully verified. The reliability of model results therefore depends heavily on site specific conditions and the ability to account for them adequately in the coefficients supplied to the models. Much professional judgement is required.

There are basically two types of model used for simulating groundwater flows. In a direct model, the physical data of the aquifer and water boundary conditions are entered and flows are calculated. When the aquifer data are uncertain, an inverse model can be used in which the permeability of the rock structure is calculated from flow data actually measured or assumed for simulation purposes.

3.5.7. Marine oil spills

The fate of oil in the marine environment is governed by the following principal mechanisms:

- Evaporation
- Dissolution
- Adsorption
- Entry into sediments.

The spread of an oil spill (and its effects) can be estimated using the US Department of the Interior’s Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME) [67]. This model provides a standard and simplified approach for estimating oil dispersion and its impacts. Data files are available for many regions in the USA but they would have to be developed for any other region.

If data on other regions are unavailable, then a judgemental assessment is necessary to estimate the impacts of an oil spill. This assessment should take into account the marine environment and marine population in the region of concern, compared with those for which data are available. NRDAM/CME can be run for various spill sizes and in different US marine regions to gain an idea of the range of possible impacts. These results could give some indication of the magnitude of impacts in a region of concern outside the USA. A subjective scaling factor can be used to adjust the aggregate impacts calculated with this model.

3.5.8. Simplified methods

The methods that have been mentioned thus far in Section 3.5 involve models that calculate the quantity of pollutant dispersed to different locations. These models are run on personal computers. Several are complex and require considerable technical expertise. Some have just recently been developed and have had limited use. Most of them require considerable amounts of data. For these reasons, it may not be possible or practical for a study to use these models. This section discusses possible strategies in this case. The discussion is not intended to cover every possibility, but rather to indicate different types of approximations and strategies to consider.

3.5.8.1. Airborne pollutants

If no models are available to simulate the airborne dispersion of primary pollutants such as particulate matter, then recent research suggests that it is possible to approximate the changes in concentrations with a simple calculation that does not rely on dispersion modelling. Numerical simulations by Curtiss and Rabl [68, 69] have demonstrated that concentrations can be approximated by simply accounting for the magnitude of the emissions and the deposition rates of the pollutants. Results for five sites in France suggest that this formula can estimate average damage to within an order of magnitude, but site dependence is significant: it was found that the damage per tonne of pollutant can be higher by a factor of 10 or more for a source near Paris compared with a rural site on the Atlantic coast. This approximation is valid for a situation in which the prevailing wind blows the emissions inland, rather than towards the ocean, and in which the population distribution is relatively uniform, as in Europe.

The IER at the University of Stuttgart has also found it “reasonable” to approximate pollutant dispersion [70]. The numerical simulations performed by the IER were also for the European situation, as were those by Curtiss and Rabl.

If a short range dispersion model is available but a long range model is unavailable, then it is possible to approximate long range dispersion by extrapolating the short range concentrations. Figure 4 [71] illustrates that dispersion occurs over long distances and that the concentration of pollutant decreases as the distance from the source increases. The functional relationship is a smooth curve. This illustration supports the extrapolation of short range estimates if no model is available to rigorously estimate long range dispersion. Such an option should be pursued only if

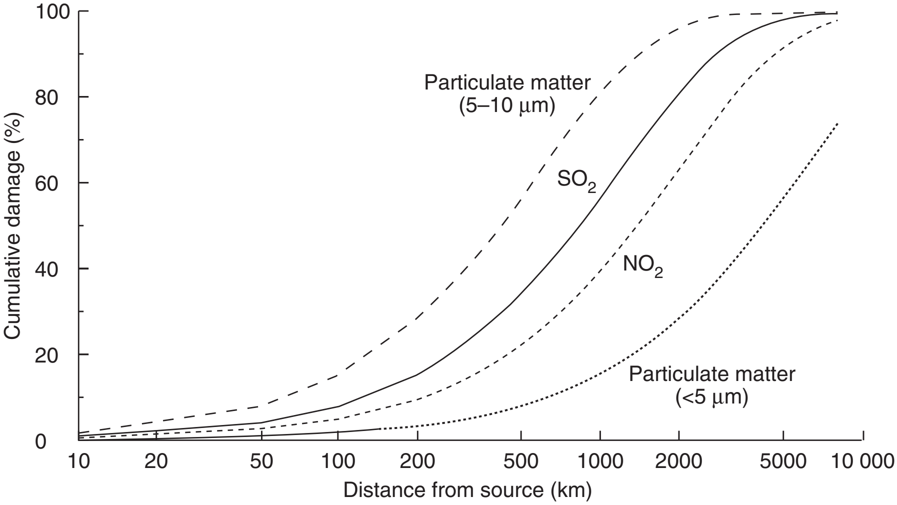

FIG. 4. Percentage of cumulative damage expected with distance from source of emissions [71].

a long range dispersion model cannot be used (e.g. because of data or resource limitations).

For example, in the US–EC Fuel Cycle Study ([9], paper 1) short range concentrations were extrapolated by statistically fitting curves to concentrations as a function of distance from the source. Different curves were fitted for each of 16 major directions to account for differences in wind velocity. The extrapolation procedure also took into account the prevailing wind direction, so that pollutants could be dispersed in all directions within the local region, and be ‘blown back’ by the prevailing wind.

In Europe, there are data collection programmes that make it relatively easy to obtain estimates of concentrations of airborne pollutants. If data on emissions are provided to the EMEP, then estimates of concentrations can be given for all of Europe. For example, data can be obtained from CORINAIR, a programme under the European Environmental Agency for establishing an emission inventory for the whole of Europe. It may also be reasonable, at least as a first approximation, to make proportional adjustments to convert national level data to a regional context.

If no models are available to represent the chemical transformation and dispersion of secondary pollutants, then this limitation is likely to be more severe than in the case of primary pollutants. Curtiss and Rabl [68, 69] have suggested that their approximating formula for the concentration of primary pollutants, discussed previously, is applicable to secondary pollutants as well. An important assumption for this to be true, however, is that the concentration of the secondary pollutant (e.g. sulphate aerosol or ozone) is a linear function of the emissions of the associated primary pollutant (e.g. SO_2 or NO_x). Some studies have, in fact, made such simplifying assumptions. However, other studies have noted the great non-linearity in these relationships.

A study by Regional Economic Research, Inc. [57], takes sulphates and nitrates to be some predetermined fractions of the SO_2 and NO_x emissions. RCG/Hagler, Bailly, Inc., and the Tellus Institute [17] assume that ozone scavenging takes place uniformly within a 50 km radius from the source of NO_x emissions. Other studies [9, 10] suggest, however, that such approximations may be too simplistic and inaccurate for some sites.

3.5.8.2. Waterborne pollutants

If groundwater plume dispersion models are unavailable, then this is probably not a major limitation. Although groundwater modelling is done in some detailed studies, none of the externalities studies to date have done any groundwater modelling [2, 10, 17]. If mine production and power generation operations are in compliance with environmental regulations, then there does not appear to be any evidence that there will be any environmental impacts of significance, at least for the US context [10].

If coastal marine models to model oil spills are unavailable, then analysts may have to rely on the results of previous studies. In this case, the extent of dispersion and amount of damage should be compared with the size of the spill. This is a general strategy that may be useful for many other types of source term and pathway. For example, one can consider using the estimated increase in morbidity rate associated with airborne pollutants which a previous study calculated. In using such estimates, however, it is necessary to account for the level of emissions in the previous study, and to make an adjustment for this level, relative to the emissions in the current study. Many conditions differ from site to site. In the case of marine environments, the speed and direction of ocean currents and the types of marine species differ widely between regions. Thus, great care should be taken when using results from another study. In particular, the key variables to be checked should include the velocity of the plume and the size of the population that lies in the direction of the plume. The same principle applies to air, water and soil pollution.

3.5.8.3. Radionuclides

If models are not available to simulate severe nuclear reactor and other nuclear accidents, then analysts can examine the results of previous studies and take into

TABLE X. DISPERSION MODELS THAT CAN BE USED TO ESTIMATE CHANGES IN POLLUTANT CONCENTRATIONS

Type of risk	Model
Primary air pollutants	Industrial Source Complex Long-Term (ISCLT) for annual average concentrations [74] Screening Procedures for Estimating the Air Quality Impact of Stationary Sources (SCREEN) for calculating short term maximum concentrations [75] Sector average Limited Mixing Mesoscale Model (SLIM3) for long range modelling [60] Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) regional source–receptor transfer matrix for long range modelling [76] Statistical extrapolations [9]
Sulphate, nitrates, acid deposition	Harwell Trajectory Model (HTM) for regional transport and chemistry of sulphur and nitrogen emissions ([4], section 1.4) Windrose Trajectory Model (similar to HTM) ([4], section 1.4) European Monitoring and Evaluation Programme (EMEP) transfer matrix for acid deposition [77] Sector average Limited Mixing Mesoscale Model (SLIM3) [60]
Ozone formation and concentration	SCREEN for plume height for ozone modelling [75] Biogenic Emissions Inventory System (BEIS) for ozone analysis (cited in Ref. [9], p. 3-26) Ozone Isopleth Plotting Mechanism (OZIPM-4) [61] Mapping Area-wide Predictions of Ozone (MAP-O_3) [62] Karlsruhe Atmospheric Mesoscale Model (KAMM) ([4], section 1.4)
Global temperature change from greenhouse gas emissions	Sea Level and Temperature Under the Greenhouse Effect (STUGE) [78} Dynamic Integrated Climate–Economy (DICE) [79]
Oil spill	Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME) [67, 80]
Freshwater contamination	Model of Acidification of Groundwater in Catchments (MAGIC) [81, 82]

TABLE X. (cont.)

Type of risk	Model
Radioactive waste routeing/exposure risk	Radioactive Material Transportation (RADTRAN V) [83]
Buildup and decay of radionuclides: source terms	Oak Ridge Isotope Terms Generation and Depletion (ORIGEN 2) [84]
Atmospheric transport of radionuclides	AIRDOS-EPA and other codes in CAP-88 package of computer codes [85]
Severe reactor accidents	MELCOR Accident Consequence Calculational System (MACCS) [52]

TABLE XI. SUMMARY OF ESTIMATING CHANGES IN POLLUTANT CONCENTRATIONS

Information input	Source terms, e.g. airborne emissions Other inputs for dispersion models, e.g. stack height and exit velocity
Type of analysis	Dispersion models for pollutants Use of existing data systems (e.g. EMEP) to supplement models Use of results from previous studies if no models available
Output of analysis	Concentrations of pollutants at each grid or co-ordinate location Changes in level of activity, e.g. in coal truck traffic, which lead to increased traffic accidents

account key assumptions and data from these studies. In particular, the following should be noted: (a) whether the probabilities of severe reactor accidents appear reasonable for the case under study; and (b) the population density over a wide area (of at least a 1500 km radius). In general, studies in both Europe [6, 72, 73] and North America [5, 21] using PSA of nuclear power plants indicate that the expected impacts (damages) are rather low: about 0.1 mill/kW(e)·h (1 US mill ≈ 0.8 mECU). These results reinforce the notion that if the design and operation of nuclear power facilities meet contemporary US, Canadian or European standards, then the key issue about nuclear power and its impacts lies in the public's perceptions of its risks, as discussed in Sections 3.6.5 and 5.2.2.

Table X lists dispersion models that can be used to estimate changes in pollutant concentrations.

A summary of Section 3.5 is presented in Table XI.

3.6. CALCULATION OF EXPECTED IMPACTS

This section describes the type of analysis required to estimate health and environmental impacts. That is, this section focuses on the part of the impact pathway approach highlighted below:

Fuel chain activity → Source term → **Changes in concentration → Impact**

3.6.1. Basic approach for calculating impacts

Impacts arise as a result of human and environmental exposure to pollutants and other residual burdens. The output of the analysis described in Section 3.5 is the input to the analysis described in this section. Table XII [17] lists the types of impacts that can result from different types of discharges.

The basic concept that is used to estimate impacts is the dose–response function. A comparative assessment should use the epidemiology and ecology literature to identify dose–response functions that relate changes in human health and ecology to changes in the concentrations of pollutants. The results are quantitative estimates of increased morbidity and mortality in human populations or changes to the environment such as reduced fish population, tree loss and reduced visibility in scenic areas. The different types of impacts reflect the different natures of the pollutants and receptors, as well as pathways.

Dose–response functions are not available for many changes in ecosystems. As a complementary method the critical loads approach may be used. This approach considers the capacity of an ecosystem to receive a certain pollutant deposition without suffering significant harmful effects. By comparing this capacity with the deposition received, a quantitative measure of the impact on the ecosystem may be obtained.

3.6.1.1. Dose–response functions

The dose–response function is simply an equation that relates the change Y in a receptor to a change in pollutant concentration of X: $Y = f(X)$, where $f(\ )$ is the dose–response function.

In addition to the concentrations of pollutants to which individuals are exposed, the length of exposure certainly affects the expected health impacts as well. However,

TABLE XII. TYPES OF IMPACTS THAT CAN RESULT FROM DIFFERENT DISCHARGES

Source of environmental impacts	Human health			Materials	Biological resources					Groundwater	Climate change	Visibility	Aesthetics	Other
	Mortality	Morbidity	Accidental injury		Crops/vegetation	Forests	Fisheries	Aquatic	Terrestrial					
Outdoor air														
Particulates	×	×		×								×		
SO_2	×	×		×	×	×						×		
NO_x, nitrate, NO_2		×			×	×		×				×		
Toxics, lead, mercury	×	×			×	×	×	×	×	×				
CO	×	×												
Greenhouse gas/CO_2	×	×			×	×	×	×	×		×			
CFCs	×	×		×	×	×	×	×	×		×			
Steam				×							×	×	×	
Radioactive	×	×			×	×	×	×	×					
Secondary outdoor air														
Acid aerosols	×	×										×		
Acid deposition				×	×	×	×	×	×					
Ozone (HCs, VOCs)		×		×	×	×			×			×		
Indoor air	×	×												
Surface water disposal														
Chemicals	×	×			×		×	×	×				×	
Thermal							×	×						×
Impinge/entrain							×	×						×
Radioactive	×	×					×	×						
Impoundment/passage							×	×	×				×	×
Consumption										×				×

Solid waste disposal											
Transportation			×							×	
Volume/land use								×		×	
Hazardous/PCBs	×	×				×	×		×		
Toxics in ash	×	×				×	×		×		
Radioactive: high	×	×				×	×	×	×		
Radioactive: low	×	×				×	×	×	×		
Construction/operation											
Construction			×							×	
Facility: land use				×	×			×		×	
Transmission: land use				×	×			×		×	
Transmission: EMF	×	×						×			
Explosion/accident	×	×	×								
Nuclear accident	×	×	×	×	×	×	×	×		×	
Spills	×	×	×			×	×	×	×	×	×
Decommissioning			×					×	×	×	×
Fuel acquisition											
Extraction	×	×	×	×	×	×	×	×	×	×	
Processing	×	×	×			×	×	×	×	×	
Transportation/storage	×	×	×			×	×	×	×	×	
Energy security/resource depletion											×
Use of public facilities											×

Note: Aesthetic impacts include visual blight, noise, odours and congestion. Other impacts include socioeconomic and recreation.

Source: Ref. [17], later published as Vol. 2 of EMPIRE STATE ELECTRIC ENERGY RESEARCH CORPORATION, New York State Environmental Externalities Cost Study: Report and Computer Model, Oceana Publications, Dobbs Ferry, NY (1995). The table is reproduced from p. 301 of Vol. 2.

in the types of studies to which this report pertains, analysis is rather aggregate, and data are lacking on lengths of exposure. Thus, the dose–response functions imply some ‘typical’ length of exposure (or distribution of exposure); and exposure or dose is typically measured in terms of average annual or daily peak concentrations. For example, for particulate matter, the dose is measured in terms of average concentration (μg/m^3), and no specific duration of exposure is stated, either for each individual or for the exposed population.

Y could represent, for example, the expected number of additional asthma attacks in a given year and *X* the change in ozone concentration. The purpose of the analysis in Section 3.5 was to calculate values for *X* at all grid locations under consideration. These locations represent the areas in which the grid points are located. The value of *X* is the incremental amount attributed to the source term under consideration. That is, it is the additional amount caused by the power plant, over and above the existing baseline level of pollution. Likewise the change *Y* is the expected incremental change.

Most of the dose–response relationships that are used in fuel chain studies are linear or nearly linear for small incremental changes in concentrations of pollutants. This linearity simplifies calculations [3, 9, 16].

Fortunately, much of the work of reviewing the scientific literature on dose–response functions has been done in Refs [2–21] and in other studies. Analysts can therefore take advantage of these previous studies and use the dose–response functions that they have identified. Thus, studies whose purpose is to estimate the impacts of a fuel chain should not usually have to estimate any dose–response functions themselves. These functions are to be found, at least for some impacts, in the epidemiology and ecology literature.

Of course, as new scientific studies are completed, new or revised dose–response functions will result. Analysts should therefore review the most recent literature. However, they should be careful to avoid using the first dose–response function that they happen to find, or even the latest one. They should consult a study that summarizes and reflects both the latest consensus in the literature and unresolved uncertainties or discrepancies. The scientific community is generally cautious and conservative in its acceptance of a new specific dose–response function.

This cautious attitude is related to prevailing limitations in epidemiology:

- Biological and medical knowledge does not always support causality in the observed epidemiological correlations; many studies have well established epidemiological associations in the case of SO_2 or fine particles, though not a definite biological mechanism yet; the case of NO_x remains more controversial.
- Epidemiological studies are conducted in variable contexts and their results should not be considered as universal. Extrapolation is completely valid only if the effects of all controlling variables are identified and accounted for.

— Measured health effects based on statistics (number of hospitalized persons, drug consumption, medical consumption, etc.) are sensitive to the local organization of the health care system.

In the use of dose–response functions for analysing ecological impacts, ecologists frequently decry the failure to consider cumulative effects in dose–response functions that estimate incremental changes. The concern is that environmental effects are sometimes highly non-linear in some ranges of pollutant concentrations. A single power plant may have an insignificant impact, but the accumulation of residual discharges from many power plants nationwide may have a great effect. A single increment may bring the stress above a critical load. It is important to remember, however, that impacts are measured on a per kW(e)·h basis. This unit of measurement controls for the size of the power plant being considered.

3.6.1.2. Thresholds

Thresholds, or S shaped dose–response relationships, occur when an organism has a natural repair mechanism that can prevent or counteract damage up to a certain limit. At very high doses, damage may level off [3, 9, 16]. There is even a fertilizer effect at low doses. This has been observed in the dose–response functions for the impact of NO_x and SO_2 on crops: a low dose of the pollutants can increase yield.

The issue of whether there is a threshold for a given impact is crucial and is discussed in several places in this report (Sections 3.6.2.2, 5.2.1 and 5.2.5.2). For example, if a linear proportional dose–response function for a given impact is assumed, a simple calculation shows that the integrated health impact of a pollutant dispersed between the ground and an inversion layer, without decay or absorption, is logarithmically infinite. Analysts must be aware of this issue.

There is inconsistency in the way regulatory bodies have considered thresholds for pollutants. The International Commission on Radiological Protection (ICRP) recommended in 1977 that no threshold be assumed for mutagenic effects or cancers caused by radiation [86]. This recommendation has been followed by almost all countries in the world. At about the same time, the US Environmental Protection Agency (EPA), followed soon thereafter by the US Food and Drug Administration (FDA), recommended that no threshold be assumed for carcinogens. Carcinogens are declared to be Class I and Class II by the International Agency for Research on Cancer (IARC). Thresholds have been implicitly assumed for other materials, such as particulate matter. Analysts should also be aware that there could be a threshold for one pollutant and health end point and not for another.

It is recommended that analysts calculate impacts with and without thresholds. For example, in one study [10], expected impacts on health were calculated to be 40%

less if a threshold for particulate matter was set at 30 $\mu g/m^3$.[9] In some regions (e.g. Europe north of the Mediterranean, including the Ural mountain region of the Russian Federation; and North America east of the Mississippi and between Richmond, Virginia, USA, in the south and Montreal, Canada, in the north), the baseline particulate concentrations are already above what many scientists believe to be the highest scientifically possible threshold. Any incremental concentration will then cause an incremental impact, whether or not a true biological threshold exists.

The threshold is important in ozone analysis because only a fraction of the days in summer have ozone levels above the threshold. Some software allows the user to specify thresholds [18, 19].

One of the limitations of most dose–response functions is that they do not account for synergies; for example, the effects of acid rain on forests depend on the composition of the soil and the interaction with other stresses such as parasites and drought.

3.6.1.3. Critical loads approach

Another approach that may be considered when dose–response functions are not available is the critical loads approach. The critical load is defined as a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specific sensitive elements of the environment do not occur, according to present knowledge [87].

The critical loads methodology has been applied to estimate the critical thresholds of forest ecosystems under the influence of sulphur and nitrogen depositions as a result of SO_x and NO_x emissions. The deposition of these pollutants can modify the chemistry of the soils owing to their acidifying character. The soil acidification can result in the mobilization of certain chemical elements such as Al, which is toxic to plants and inhibits the uptake of base cations (Ca, Mg and K), and thus have a detrimental effect on the forest. The critical loads methodology determines the quantity of acidifying compounds that an ecosystem can receive without the chemical characteristics of the soils being changed. Furthermore, this method can be used to estimate the sensitivity of forest to the indirect effects of the deposition of acidifying compounds.

Critical loads may be calculated for different pollutants and receptors as a site specific methodology, considering different characteristics such as soil, vegetation,

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[9] This threshold is specified in terms of total suspended particulate matter (TSP). Section 5 suggests that PM_1, or if this is unavailable, PM_{10} be used as the measure of particulate air pollution. A threshold of 30 $\mu g/m^3$ TSP corresponds to a threshold that is less than 30 $\mu g/m^3$ for smaller particles such as PM_1 or PM_{10}, which are subsets of TSP.

precipitation, temperature, base cation deposition, weathering rate and nutrient uptake. Several models have been developed for the estimation of critical loads. These models evaluate physical and chemical processes in soils or water, depending on the pollutant considered. They may be steady state, such as PROFILE [88] and the Steady State Mass Balance (SSMB) model [89], or dynamic models, such as the Model of Acidification of Groundwater in Catchments (MAGIC) [81, 82] or the Stimulation Model for Acidification's Regional Trends (SMART) [89].

These models assume an equilibrium between the input and consumption of acid compounds in forest soils and water in such a way that the maximum estimated input of the acidifying compounds does not cause exceedance of the threshold and therefore modify the chemical properties, causing damage to the ecosystems.

3.6.2. Impacts on human populations

3.6.2.1. Types of health impact

Human health impacts are usually categorized into:

- Increased rate of mortality
- Increased morbidity and injuries.

These impacts are estimated in terms of statistical expectations. The exact numbers of deaths, illnesses and injuries are unknown (even after the fact). It is generally impossible to specify that a particular individual died prematurely because of exposure to a particular pollutant. However, exposure does increase one's risk of morbidity and, in some cases, premature mortality. This risk, as measured in terms of the probability of an event multiplied by the magnitude of the impact if the event occurs, is a measure of the impact of a fuel chain.

Human health impacts can also be categorized as:

- Public, or
- Occupational.

The distinction is important for at least two reasons. One reason is that the source of data and the nature of the calculations differ for the two types of impacts. Public health impacts are generally estimated by estimating the magnitude of the exposure (e.g. through air dispersion modelling of emissions) and using dose–response functions. Occupational impacts can be estimated, to a large extent, from historical data on occupational accident rates. Analysts should take care to account for regulatory or other changes that can make historical rates less relevant for estimating future accident rates. It should also be noted that public and occupational health impacts from a risk source can be different owing to a possible age dependence of these effects, as in the case of ionizing exposure, for example.

The second reason is connected with the estimation of externalities (Section 4). In many cases, occupational risks are factored into wage rates. In these situations, much of the impact and associated economic damage are internalized and are not externalities. Impacts to the public at large, however, are generally externalities, unless the damage is offset or otherwise accounted for by the market, such as through insurance.

Health impacts can be produced through different pathways. In a comparative assessment, some but not all of these pathways should be analysed (Section 3.3). The common practice is that inhalation pathways are considered and that ingestion pathways are generally not considered. The main reason for focusing on inhalation pathways is that human exposure to fuel chain pollutants is likely to be from airborne pathways (i.e. inhalation of pollutants), rather than by ingestion through the skin or food. The other reason is that there is more scientific information to draw on; much less research has been done on ingestion exposure and dose–response functions. Where there is evidence of significant ingestion, however, this pathway should be examined to the extent possible. Physical injury in accidents should be considered as well. Thus, the basic types of health effect considered in impact assessments include the following:

(a) Mortality and morbidity among the public from inhalation of airborne pollutants released as a result of:
  - Production of materials needed for construction of the power plant and related facilities;
  - Extraction of fuel and its transportation to the plant;
  - Plant operation, including maintenance and accidents in operation of the plant and associated facilities;
  - Waste management and disposal;
  - Plant decommissioning and demolition, and recultivation of the plant site.

(b) Occupational fatalities and injuries in:
  - Production of materials needed for construction of the power plant and related facilities;
  - Extraction of fuel and its transportation to the plant;
  - Plant operation, including maintenance and accidents in operation of the plant and associated facilities;
  - Waste management and disposal;
  - Plant decommissioning and demolition, and recultivation of the plant site.

(c) Impacts on the public of transportation accidents (both fatal and non-fatal).

(d) Different types of cancer in the case of severe reactor accidents.

Other impacts, such as the relocation of people, should also be considered. These are particularly important in the analysis of energy options involving large scale land use, such as hydropower or open pit mining, but may also appear in the development of other types of energy resources. In this context one might also include evacuation ancillary to an accident at a power plant, during fuel transportation or at a fuel storage facility. Relocation and evacuation may themselves have a significant effect upon health, in addition to public inconvenience, financial expenses and lost time and productivity.

In view of the differences between various energy technologies it is essential to consider all the stages of the fuel chain for each energy source and to determine which stages contribute significantly to the impacts of a given option. It is usually insufficient, and usually misleading, to compare only those hazards which are connected to power plant operation without mentioning the impacts of the other stages of a fuel cycle, which may give a higher contribution to the overall impact of a given option. Similarly, it is not correct to restrict the risk merely to that of accidents, since often illnesses among miners or the public can represent a much greater contribution to risk in general. All important impacts within the preselected boundaries and scope of the study should be considered.

3.6.2.2. Effects of thresholds

The use of thresholds in dose–response calculations significantly affects the estimates. If a threshold is used, then the estimated impacts might be significantly less than the estimates when no threshold is used. The no-threshold hypothesis for dose–response functions means that long range, very low level impacts are included in the impact assessment. For instance, very fine particles or gaseous radionuclides discharged into the atmosphere can spread over very long distances (well beyond 1000 km), inducing small individual impacts on a large number of people. Such low impacts are then added, producing a significantly large collective risk value. In such cases, a paradoxical conclusion is derived: while each individual experiences a negligible exposure and consequently a negligible risk, a significant total collective health impact is calculated. In the case of radionuclides, this conclusion reflects the idea that extremely low exposure still increases the risk of cell mutation that will lead to a neoplasm (cancer), and that if a great many people are exposed to small doses, then there is a non-zero probability that a few of them will develop cancer, though most will not.

In the case of radiological exposure, the concept of ‘collective dose’ is commonly applied: that is, the sum of individual doses can be directly derived from the dispersion of radionuclides in the biosphere, without calculating each individual dose [90]. However, for the situation where the range of individual doses spans several orders of magnitude, it was recently recommended by the US National Council on Radiation Protection and Measurements (NCRP) [91] that

> "the distribution should be characterized by dividing it into several ranges of individual doses, each covering no more than two or three orders of magnitude, with the population size, mean individual dose, collective dose and uncertainty being separately considered for each range".

It is questionable whether a collective dose with negligible individual risks should be put on the same scale as a local dose with non-negligible individual risks.[10]

The same NCRP report [91] emphasizes that projection of collective committed doses to future populations and situations should be done with care, because large uncertainties are introduced by largely unpredictable changes in relevant parameters: ecology, demography and way of life.

3.6.3. Impacts on the natural environment

There are many potential ecological impacts, but limited scientific knowledge frequently precludes quantitative estimates at the regional or local scale. The ecological impacts that are typically considered include:

- Reduced crop yield;
- Impacts on natural vegetation and forests;
- Reduced freshwater fish population;
- Impacts on recreational and commercial fishing;
- Impacts on marine resources due to oil spills;
- Impacts on biodiversity (e.g. hydropower projects may decrease biodiversity, while biomass activity may increase it);
- Reduced visibility from haze.

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[10] An interesting example of such a situation is given by the Chernobyl accident. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated the total collective dose commitment (for the world) from the accident to be 600 000 man·Sv [92]. Most of this collective dose is from globally incurred, very low (practically negligible) individual doses. The regional and the local dose commitment are part of this total. This part results from considerably higher individual doses, but is lower by an order of magnitude (~50 000 man·Sv). Only this latter risk is the object of radiation protection activity. The global part of the collective dose is not addressed by any decision making on population protection or responsibility for damage.

Except for unique resources, such as archaeological sites, waterfalls and endangered species, the incremental addition of a single power plant is unlikely to have a major impact on an ecosystem. However, the accumulation of stress to the environment resulting from many plants may cause a non-linear, threshold attaining or catastrophic reaction in an ecosystem.

Environmental impacts can be categorized as follows:

- Natural environment:
  - Effects on fauna, forests, lakes, etc.;
  - Aesthetic effects;
  - Increased noise.
- Agricultural environment:
  - Effects on crop yields.
- Physical environment of human origin:
  - Effects on roads;
  - Effects on buildings;
  - Effects on artefacts and historical monuments.

3.6.4. Accidents and risks

As discussed in Section 3.5.5, accidents are among the impact pathways that a comparative assessment should address. There exists the potential for many types of accidents at various stages of a fuel chain. The types of accidents whose impacts should be considered are:

- Accidents involving occupational injuries and fatalities;
- Transportation accidents involving public injuries and fatalities;
- Transportation accidents involving ecological impacts (e.g. oil spills);
- Severe accidents involving impacts on human health, ecology and infrastructure.

Studies should consider both the more common accidents that inevitably occur in the course of industrial activities and the potential for infrequent but severe accidents with major impacts. Impact assessment is based on the expected damages approach, where potential losses in the event of an accident are multiplied by expert estimates of the probability of the accident.

The potential losses are conditional on the accident occurring. For the more common types of accidents, estimates of these conditional impacts can be derived from historical data on fatalities, injuries and other health effects that occurred when an accident took place.

The concept of risk, as commonly used in nuclear fuel cycle analysis, encompasses both the probability of an event occurring and its consequences should it occur. For the nuclear fuel cycle, the common risk analysis approach is as follows:

- Carry out a PSA, producing data on probabilities of accidents of various types and consequences;
- Calculate the damages that result from a possible accident, using software such as COSYMA [51], developed by the EC to study nuclear accidents.

Where possible, risks should be estimated from available empirical data, using engineering judgement if necessary. For common types of accidents, sufficient experience and data may exist to justify using empirical data to estimate the mathematical expectation of the damage (i.e. the estimated probability multiplied by the conditional damage). For low probability/high consequence accidents, however, insufficient empirical data exist, and there is greater reliance on experimental data and engineering judgement (Sections 3.5.5 and 5.2.2 contain additional discussion).

In addition to the damages caused by any accident, there are accident prevention and emergency response costs:

- Costs of engineering and other measures to prevent accidents;
- Costs of mitigating the consequences of accidents, should they occur.

The costs in the first of these categories are part of the capital investment and operation and maintenance costs, and are internal costs. Costs in the second category may be internal or external (Section 4.5.1), depending on the institutional structure in the country concerned. In the USA, for example, the Price–Anderson Act requires utilities to carry insurance against nuclear power plant accidents. This type of mechanism provides an element of insurance not only explicitly for the utility but for the national economy as a whole, which may be at risk in the event of a severe accident. The notion of internalizing externalities pertains across all fuel chains. Other examples are given in Refs [8–10].

3.6.5. Public perceptions of risks

Certain types of risk, for example those associated with the possibility of a severe accident or exposure to electromagnetic fields, give rise to heightened public awareness and concern, sometimes out of proportion to the calculated estimates of risk. Individuals also demonstrate aversion to these risks based on their perception of the magnitude of the risks. This can lead to stress and reduced quality of life for some individuals, which may influence behaviour and increase their willingness to pay to avoid such risks.

These psychological impacts are regarded as different in nature from the direct impacts due to accidents or emissions. Analysts may wish to consider the issue of public perception and aversion in a comparative assessment but are cautioned to keep impacts associated with perceived risks separate from engineering based estimates of risk. In any such approach care should be taken to ensure consistent application to all risks for which it may be relevant. It should also be recognized that the same opinions and perceptions may influence any subsequent decision process on alternative energy systems to which the results of comparative assessment provide input.

A further discussion of the treatment of risk perception as a possible contribution to impact or externality calculations is provided in Section 5.2.2, although an accepted model and supporting data for such treatment remain to be established. The issues of public perception and aversion of risk are frequently raised in the context of the nuclear fuel chain, but they apply to other fuel chains as well (Sections 3.5.5 and 5.2.2).

3.6.6. Global climate change

There is no doubt that burning of fossil fuels inevitably increases the emission of carbon dioxide. This has clearly been responsible for an increase in concentration of CO_2 in the atmosphere. About half of the CO_2 emitted stays for a period of 50–200 years. There is no doubt that, as noted by Fourier in 1835, the Earth is a greenhouse. What is in doubt is the extent of the change due to anthropogenic emissions. In 1896, the Swedish chemist Arrhenius made the first good calculation of the relationship between CO_2 concentration and average global temperature rise. In recent times this has been followed by extensive computer calculations. The work has been reviewed in an ongoing international study by the Intergovernmental Panel on Climate Change (IPCC). The first report in 1990 [93] suggested that a doubling of atmospheric CO_2 concentration would lead to a temperature rise of 1–5 K and that this was likely by the year 2030. The second, in 1996, was less pessimistic [94–96]. In its most recent report [94], the IPCC reduced the upper range of its estimate of the average increase in temperature from 5 to 4 K and extended the date of when this would occur to 2050. However, the computer calculations fail to describe the temperature history of the last two centuries, and in particular the last twenty years, when fossil fuel burning has been extensive, so that skeptics often suggest that the effect is zero.

Estimates of impacts on ecosystems and on agriculture are even more difficult to determine than the projected average increase in global temperature. For example, several factors contribute to variations in sea level. Recent and projected increases in sea level, which are being attributed to climate change, are probably of the same order of magnitude as some natural variations over the last several thousand years [94].[11]

It is generally agreed that most health or environmental impacts are related directly to the temperature rise and to the increased probability of extreme events such as droughts and floods, and not to the CO_2 concentration increase directly. While analysts should include global climate change in impact assessments, they should be aware of the limited precision of the information. The effect on a comparative environmental analysis is to emphasize the advantages of non-fossil fuel technologies and to de-emphasize those of fossil fuel technologies.

When oil is burned some of the heat is from combustion of the hydrogen, and when natural gas is burned even more comes from the hydrogen. Therefore, natural gas is often preferred to coal from the point of view of global climate change. However, natural gas (CH_4) is itself a greenhouse gas and any leakage of the gas anywhere along the fuel chain from its extraction to the burner can contribute to global warming.

The monetary valuation of the impacts of global climate change is even more controversial. Further details are given in Appendix I.

3.6.7. Ozone depletion

Stratospheric ozone depletion, in contrast to tropospheric ozone formation (Section 3.5.4), is not primarily an energy issue, though there are several potential causal gases that are related to the energy industry (such as refrigerants used in cooling systems and N_2O formed in the burning of biomass). Ozone depletion is one of the most important issues in terms of globally sustainable development. Depleted ozone leads to increased ultraviolet radiation at the Earth's surface, which may affect both aquatic and terrestrial environments, as well as human health.

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[11] However, the recent rise in sea level attributed to global warming is considered to be part of a sustained trend, whose effects will accumulate as greenhouse gases accumulate in the atmosphere. The projections suggest that sea level rise in the next century could be 1.5–5.5 times what it has been in the last century (though still only on the order of several decimetres). In contrast, natural variations over the last thousand years appear to be more random, with little if any trend. Over geological time, there have been sea level changes much greater than several decimetres, e.g. those due to continental drift and ice ages, but these events took much longer to occur than the time frame of several centuries being discussed for global warming.

3.6.8. Energy security

The term ‘energy security’ refers to the economic and national security of a country that is dependent on oil imports from a supplier or suppliers with considerable market power (i.e. the Organization of Petroleum-Exporting Countries (OPEC)) or that is vulnerable to oil price shocks, or both. Energy security is not specifically an environmental issue, but since it must be considered pari passu with environmental issues it is briefly considered here and a fuller description is provided in Appendix II. There are two aspects to energy security. One aspect is that of a quasi-steady state. The other is characterized by ‘catastrophic’ disruptions in oil supply and national security concerns.

3.6.8.1. Economic costs during quasi-steady states

The quasi-steady-state impacts are more easily discussed in terms of basic economic theory (Appendix II). Energy security costs may exist for an oil importing country when its economic welfare is not as great as it could be if the oil market were efficient. The magnitude of these costs depends on the degree of market power that OPEC possesses and on the ability of the oil importing country to respond.

Energy security costs, to the extent that they exist, have two major components. One component is the economic rent that OPEC extracts from the market through its power as a cartel. The other component occurs when there are sudden changes in the price or availability of imported oil. These price shocks result in spillover effects on the total performance of the economy, which are not reflected in market prices, as the economy adjusts to the disruption in oil supply.

Analysts differ greatly in their assessments of the magnitude of these costs. There are basically two positions. One position is that these costs are significant. The other position is that they are not or, at least, that they are not relevant to policy. This report does not attempt to resolve this issue, but rather to summarize the positions, and thus the state of the literature on energy security costs. Proponents of each position agree on the need for more detailed analysis on key points of contention.

3.6.8.2. Energy security and catastrophic events

Many countries, particularly those without energy resources of their own, must consider the possibility of a catastrophic effect of energy insecurity, whether caused by a natural disaster or by external political pressure. These countries might decide to store fuel for many years near the power plant, leading to increased cost and environmental problems. This may also influence the choice of fuel and favour a high energy density, easily stored fuel such as uranium, instead of a lower energy density, less easily stored fuel such as oil or gas. Analysts must be aware of the possible health and environmental impacts of these actions.

3.6.9. Impact indicators

Different impact indicators are required because the nature of impacts varies considerably. They generally cannot be reduced to a single measure.

The severity of an impact can be measured by different types of indicators:

(a) Direct measure of the expected impact, e.g. expected increase in annual mortality;
(b) Likelihood of exceeding critical loads, beyond which there are deleterious effects on species or ecosystems;
(c) Risk of an impact if there is significant uncertainty about its likelihood;
(d) Quantity of emissions that eventually lead to the impact, assuming a monotonic relationship (ideally linear) between emissions and impact;
(e) Indicator of the impact on some scale (determined subjectively by expert judgement), in cases where the impact cannot be measured or estimated;
(f) Economic damages or cost of the impact.

A direct measure has the advantage of describing most straightforwardly the nature and extent of the impact on the receptor. The disadvantage is that the unit of measurement varies for each type of impact. For example, one unit of measurement could be the number of ‘restricted activity days’ for individuals, another measure could be the number of fish killed, and yet another, the degree of reduced visibility at 3 km in the vicinity of the power plant. The use of different indicators makes it very difficult to undertake an overall assessment of the impacts of a fuel chain and to make decisions on the basis of these impacts.

The use of an economic measure has the advantage of reducing many different types of impacts to a common metric, thereby facilitating comparative assessments (Section 4.2.1). Economic measures also have the advantage of facilitating the comparison of options that must be assessed on the basis of their benefits relative to their costs. A disadvantage of using economic measures is that the economic value of items that do not have markets (e.g. ‘statistical’ lives) is frequently not understandable or convincing to people.

Impacts that cannot be measured either directly or in terms of their economic value should still be considered to the extent possible. This may mean using the magnitude of the emissions that would lead to an impact as a surrogate measure of the impact, or even just a description of the impact. All important impacts, regardless of how they are measured, should be considered in any integration of impacts and assessment of fuel chain options. Section 4 provides further discussion on this point.

3.6.10. Impact parameters

There are different ways of categorizing impacts that are useful for different contexts:

(a) *Time frame.* Impacts are frequently divided into three categories: short term or acute; lifetime; and intergenerational.
  (i) Short term or acute effects are those that occur within a year. Examples are respiratory attacks that occur when tropospheric ozone levels are very high, reduced crop yields due to raised ozone levels, injuries to fish in hydropower projects, reduced visibility from air pollution, noise from wind turbines and occupational injuries.
  (ii) Effects that occur over the lifetime of individuals might include cancer deaths resulting from a severe nuclear reactor accident or respiratory deaths due to long term exposure to air pollution. Effects such as damage to monuments, buildings and other structures from long term exposure to air pollution, and damage to forests from long term exposure to acid precipitation are effects in which there is damage from long term accumulation of exposure to pollutants. With these somewhat longer time frames, it is advisable to quantify the uncertainty in the estimates of impacts (Section 3.7).
  (iii) Intergenerational impacts are those that are caused by any stage of a fuel chain and arise far into the future. With such a long time frame, much greater uncertainty can be expected in the estimates of impacts. Examples of such impacts are those from global climate change and those due to releases of radionuclides or other materials from nuclear or other waste repositories. Some analysts prefer not to monetize longer term impacts because of the great uncertainty associated with these impacts.
(b) *Frequency.* Impacts can be categorized as either relatively frequent or of low probability but high consequence.
  (i) Most impacts occur on a continual basis, arising from continuous emissions from the power plant. They can also result from accidents that are frequent enough that historical data provide a reasonable estimate of their probability.
  (ii) For the other type of impact, accidents that are very unlikely, historical data are either non-existent or, if they exist, are of little use in predicting the likelihood of such events in the future. A prime example is a severe nuclear reactor accident.

  The difference between these two types of impacts is important psychologically. Therefore, they should be kept separate in any analysis

TABLE XIII. SUGGESTED LISTING OF IMPACTS IN SEPARATE CATEGORIES[a]

Geographical scale	Time frame		
	Short term (1–2 years)	Lifetime	Intergenerational
Local (e.g. local jurisdiction or within 50 km)	x_{ls}	$x_{l\ell}$	x_{li}
Regional (e.g. national)	x_{rs}	$x_{r\ell}$	x_{ri}
Global	x_{gs}	$x_{g\ell}$	x_{gi}

[a] Magnitude of impact represented by value x.

and presented separately in a final summary so that the decision maker is aware of them.

(c) *Geographical scale.* Impacts can occur on a local, regional/national or global scale. It is important to consider the locations of impacts when estimating their economic value because it may be appropriate to use different values for different regions to reflect different income levels. Identifying the locations of impacts is also important in a policy context, since discharges from one political jurisdiction may result in impacts in another jurisdiction.

One informative way of summarizing results is in the form of a matrix, as illustrated in Table XIII. Results are listed separately according to whether they are expected to occur in the short term, during the current lifetime or to future generations. Results are also similarly listed according to whether they are expected to occur locally, regionally (e.g. nationally) or globally. This type of arrangement provides more detail than an overall cumulative summary, but it also reduces the degree of controversy associated with issues such as intergenerational discounting by not forcing all impacts into a single measure.

3.6.11. Accounting for future changes

The impacts of fuel chains will change in the future. Thus, estimates of impacts that are based on current data may not be accurate indicators of impacts in the future. It is important that any study of the impacts of fuel chains acknowledge this possibility.

One source of these changes is technological progress. Power plants will become more efficient, with higher capacity factors. The efficiency of pollution abatement equipment will improve as well. Thus, emissions from power plants to be constructed in the future will, other things being equal, be less than current emissions. Even for existing power plants, it is likely that improvements and backfits will reduce their emissions (on a per kW(e)·h basis). One way of addressing the problem of estimating future impacts is to use the best available data on future emissions. Frequently, such data do not exist. An alternative approach would be to use engineering judgement to assume reasonable reductions in emissions, and to do a sensitivity analysis (Section 3.7).

A second reason why future impacts will be different from current impacts is that medical technology will advance, reducing the susceptibility of different populations to various health conditions. Thus, the type and extent of the human health effects of fuel chain activities may change from current levels. These changes would have the effect of changing dose–response relationships. It is difficult, at best, to anticipate improvements in medical technology. Thus, one option for addressing this uncertainty is simply to assume that the dose–response functions are unchanged. The other option is to specify some percentage decrease, such as 20%, in the degree of response (i.e. impact on health or the environment) for a given level of exposure.

A third way in which impacts may change is that the background levels of air pollutants may change. The background levels are important when there are thresholds to health or ecological effects from exposure to pollutants. If background levels are much less than the threshold, then an increment in pollutant concentrations is unlikely to cause any impact. As in the previous discussion, it is difficult to predict future background levels. Analysts would have to make an assumption that background levels are unchanged, some percentage greater than current levels (e.g. owing to greater industrialization if the comparative assessment were for the situation in a developing country) or some percentage less than current levels (e.g. as a result of more stringent environmental legislation).

A fourth reason why impacts may change in the future is that the size and geographical distribution of the population will change. In most calculations the population size and distribution are assumed to be unchanged from current levels. However, if the local region is likely to grow significantly, then data on population growth rates are frequently available from the government department responsible for the census or from similar departments or ministries. These data can be used to ‘inflate’ the population estimates by some percentage on an annual basis. Some countries even have projections for individual regions. This adjustment is more important in developing countries with high population growth.

A fifth source of change is that land uses (e.g. for agricultural crops and forests) may also change in the future. Thus, the magnitude of the impacts on these

TABLE XIV. SUMMARY OF IMPACT ESTIMATION

Information input	Incremental changes in concentrations of pollutants, or other incremental changes (e.g. noise)
Type of analysis	Use of dose–response functions based on results in the epidemiology and ecology literature
Output of analysis	Numerical estimates of the impacts

ecosystems will change from the current impacts, depending on how much the ecosystems change. As in the previous discussions, the default approach is to assume that there is no change. This is the standard approach taken in all of the major fuel chain externality studies thus far.

A summary of Section 3.6 is presented in Table XIV.

3.7. UNCERTAINTY AND SENSITIVITY ANALYSIS

The purpose of this section is to summarize how uncertainty arises in comparative assessments, to list some ways of providing information on uncertainty and to discuss the usefulness of sensitivity analysis. Section 5.2.5 provides further discussion on these topics.

3.7.1. Sources of uncertainty

There is a significant degree of uncertainty in most estimates of impacts. The uncertainty in quantitative estimates, in particular, is as much a general finding of recent studies as it is a limitation of them. This uncertainty reflects the state of knowledge in each scientific discipline that is drawn upon in implementing the impact pathway approach. The overall uncertainty about the size of an impact is compounded through each subsequent step of the impact pathway analysis.

Thus, even the best studies will have sizeable uncertainties associated with their results. The types of uncertainties include: statistical uncertainties represented as confidence intervals; and unquantifiable uncertainties associated with data and sampling issues, model specification and functional form. Statistical uncertainties can result in a range of several factors in magnitude, and even an order of magnitude or more. The uncertainty that arises from a lack of understanding of a phenomenon is generally even greater than this. A prime example is that associated with the long term effects of global climate change.

3.7.2. Providing information on uncertainty

There are many ways of indicating the degree of uncertainty in estimates of impacts. These include:

(a) Identifying statistical and judgemental confidence intervals for many components of the analysis; however, the confidence intervals that are calculated do not account for the full range of uncertainty.

(b) Combining uncertainties in many of these components to develop probability distributions of damages and benefits for many of the impact pathways, and aggregating these distributions across pathways to develop overall damage probability distributions using Monte Carlo simulations ([10], section 4.8.1).

(c) Presenting an uncertainty message system such as that developed by Funtowicz and Ravetz [97]; this system offers a structured way for analysts to appraise the quality and uncertainty of the data that they use to estimate impacts, damages and externalities (part VI of Ref. [9] illustrates the use of this system).

(d) Using symbols, such as partly or wholly filled circles, to display the degree of confidence in a particular estimate (e.g. Ref. [10], tables 11.4-1 and 11.4-2).

(e) Providing information and explanation for the uncertainty in the estimates (e.g. in the discussions of global climate change in Ref. [10], section 10.2).

(f) Calculating and presenting low, medium and high estimates that reflect the range of values that affect the final estimates of the total impact; if the study context indicates that a conservative estimate of impacts is desirable, then one can use the high estimate; otherwise one should generally use the medium estimate.

3.7.3. Identification of key results

A fuel chain can have many impacts. In assessing fuel chain options, it is important to focus on the more important impacts. Thus, it is important to concentrate on identifying the factors that affect the final results the most.

Sensitivity analysis is an important tool for estimating the range of uncertainty in estimates and the effects of certain assumptions and key parameters on these estimates. It typically involves selecting certain assumptions or parameters to study and varying their value over a plausible range in some systematic way. Each set of input data values leads to a different set of results. These results can be tabulated and graphed to indicate the relative importance of different assumptions, as well as the range of impact estimates.

A summary of Section 3.7 is presented in Table XV.

TABLE XV. SUMMARY OF UNCERTAINTY AND SENSITIVITY ANALYSIS

Information input	Scientific literature on the impact under consideration Information about the nature of dispersion models Standard errors and similar statistics for dose–response functions Standard errors and similar statistics for economic valuation functions
Type of analysis	Estimation (if only qualitative) of the order of magnitude of the uncertainty of the impact Monte Carlo simulations to generate probability distributions for magnitude of impact ‘What-if’ calculations using plausible ranges of values for parameters and other factors that affect the final estimate of the impact
Output of analysis	Qualitative and quantitative estimates of the nature and size of impacts Probability distributions generated by Monte Carlo analysis and sensitivity analysis

3.8. SYNTHESIS OF RESULTS

After the impact indicators have been calculated or estimated, it is useful to synthesize these results. Synthesized results assist in comparing energy options and in highlighting their overall differences.

Summary tables that tabulate estimated impacts are useful. However, they may also be misleading in that other important information, not included in the tables, might be overlooked by readers. Depending on the issue at hand and the scope of the study, it might not be very useful to have only a tabulation of all of the numerical results for each separate impact pathway. For example, ozone has many different types of respiratory health effects. A simple tabulation of all numerical results may obscure an important finding, for example that in aggregate, ozone formation has major consequences for human health compared with, say, lead emissions.

Even though impacts are measured in many different ways, it is possible to synthesize results by defining categories and by tabulating aggregate impacts in each category. An example is the following list of categories:

- Increased risk of mortality (expected number),
- Expected increase in morbidity among the public,

TABLE XVI. SUMMARY OF SYNTHESIS OF RESULTS

Information input	Estimates of impact indicators for detailed impact pathways
Type of analysis	Definition of categories of impacts and/or conversion of some impact indicators into economic measures
Output of analysis	Summary tabulations of impacts in each category, augmented with qualitative information about impacts that cannot be quantified

- — Expected total number of occupational injuries,
- — Expected severity and type of major ecological damage.

These impacts could also be summarized separately for each major stage of the fuel chain. This information could be useful for determining which parts of the fuel chain deserve the greatest attention to reduce their impacts.

If impacts are translated into an economic measure, then it is possible to sum their monetary values. Estimates may be listed according to geographical and time frame categories (Table XIII). Monetary estimates have different degrees of quality and uncertainty. To some extent, this uncertainty can be reflected through high/medium/low, Monte Carlo or numerical unit spread assessment pedigree (NUSAP) methods. More importantly, one should be aware that many impacts are likely to be omitted if only impacts with economic measures are included.

Many indicators cannot be simply added together. One of the great advantages of using economic damages as an indicator is that the nature and magnitude of the environmental impacts are expressed on a common basis. However, it is difficult to estimate the value of some impacts in monetary terms. Nevertheless, some indicator of these impacts should be explicitly listed so that they are not overlooked. Multicriteria evaluation methods [98, 99], discussed in Section 4, are a useful way of synthesizing the overall severity of impacts that are measured in different ways. Other considerations (e.g. financial) that should also be included in assessing fuel chain options are also discussed in Section 4.

A summary of Section 3.8 is presented in Table XVI.

4. CALCULATION AND USE OF IMPACT INDICATORS FOR COMPARATIVE ASSESSMENT

There are a number of methods which can be used to compare the health and environmental effects of electricity generation options and to integrate them into planning and decision making processes. The methods include: comparison of these effects on a qualitative basis using descriptions of potential damages and professional judgement; comparison based on units of emission; monetary valuation of environmental effects; and 'valuation' through the use of weighting and/or ranking within a multicriteria assessment framework. This report recommends the use of all of these methods, as long as they satisfy the requirements of the study.

4.1. REASONS FOR ESTIMATING ALTERNATIVE IMPACT INDICATORS

The primary 'impact indicators', which analysts should attempt to estimate, are the specific impacts themselves. However, it is usually advisable to estimate other impact indicators. This need for additional indicators depends on the scope of the study (Section 3.2.1). Thus, there are several possible reasons for analysis beyond impact pathway analysis as described in Section 3. These reasons can include any of the following:

(a) The analyst thinks it worth while to have supplementary indicators of the health and environmental effects.
(b) Impact pathway analysis was unable to quantify all of the important impacts.
(c) The impacts are expressed in different units (e.g. expected increases in different types of health conditions, crop loss, effects on fish population and reduced visibility due to haze), making it difficult to compare their relative severity and therefore to compare energy options.
(d) It is desirable to have a summary measure (or measures) of the overall impacts.
(e) It is desirable to indicate the economic value of the impacts because pollution prevention and abatement decisions or policies that will increase the costs of generating electrical power are being considered.
(f) Assessments are to be made of the extent to which health and environmental damages are not yet reflected in the market price of electricity.

The sequence that this report recommends is as follows:

(1) Impact pathway analysis, as described in Section 3, to estimate impacts;
(2) Calculation of impact indicators using a combination of economic valuation, multicriteria analysis (MCA) and possibly other methods, as described in this section;
(3) Comparison, first of the discharges and the magnitudes of the corresponding impacts, and then of the impact indicators, across the fuel chain options under consideration.

This report does not suggest that economic valuation must be done. Rather, it is suggested that, depending on the scope of the study, economic valuation could be a useful way of reducing the number of different measures of impacts and of expressing impacts in economic terms. The report also suggests that economic valuation and MCA be used in combination, rather than as alternative methods.

4.2. EXPRESSING IMPACTS AS ECONOMIC DAMAGES

This section describes the type of analysis required to estimate the economic value of health and environmental impacts. Economic valuation, if deemed appropriate for the study, extends the impact pathway approach of Section 3 and adds another step to the analysis as highlighted below:

Fuel chain activity → Source term → Changes in concentration → **Impact → Valuation**

4.2.1. Economic damages as an indicator of the value of an impact

The first step in the economic analysis translates the estimates of impacts into economic values, which are measured according to a common metric or indicator. These values reflect empirical evidence on individuals' willingness to trade off or sacrifice resources (time, money, etc.). The damages associated with a particular impact are regarded as the economic value that individuals are willing to pay to avoid that impact or the risk of its occurrence.

The recommended paradigm for economic valuation is that used in modern cost–benefit analysis. In essence, something has value if it affects the 'utility' or level of well-being of individuals. The magnitude of this value can be represented by individuals' willingness to pay (WTP) to avoid the undesirable impact. The 'individuals' mentioned here are considered to be representative individuals in the population at large. These individuals have a variety of tastes and preferences, but it is assumed that they have a 'reasonable' distribution (e.g. like a normal distribution). The individuals are not those directly affected by a specific generating plant or fuel chain, nor are they stakeholders, regulators, politicians or respondents to public opinion polls. Data limited solely to individuals from any one of these groups would represent a biased sample.

In some cases, it is straightforward to estimate damages because the impacts are on items sold in a market, such as crops. When the items that are damaged have market prices, economic valuation is straightforward and is a generally accepted practice.

In many other cases, the items that are damaged are not sold in a market and do not have a well established price. Examples are recreational resources such as fishing biodiversity, different types of sickness, and death. The values of certain things such as recreational resources are frequently inferred from studies which account for the travel expenses and the value of the time spent to travel to the recreation site. In some cases, estimates of individuals' WTP for (or to avoid) these non-market impacts can be obtained, for example, from 'contingent valuation' (CV) studies (Section 4.3.1). In these studies, samples of individuals are asked carefully worded questions to elicit their responses about their WTP to avoid specific negative impacts (or to gain positive impacts).

A preferred study design would be one in which study participants are presented with alternative sets of circumstances, with each circumstance described in terms of many different types of variables. Thus, information would be gained from the participants on some of the trade-offs that they are willing to make among attributes and outcomes. Usually in CV studies, however, the questions focus on variables one at a time. Possibly the major drawback of CV experiments is that although the participants provide information about their willingness to pay for things, they do not actually have to pay for them.

To economists and others, the notion of 'valuation' inherently means 'economic', but this perception is not generally true. For example, many ecologists argue that ecosystems have intrinsic value quite apart from the direct financial benefits from the resources of those ecosystems as well as from any individual's WTP to avoid damage to them. However, a major reason for using the economic approach is that many important policy decisions explicitly involve economic trade-offs between having environmental impacts and spending financial resources to reduce them.

4.2.2. Economic valuation

As discussed previously, economic valuation, or 'monetization', is the process of standardizing estimates of impacts, which are measured in different ways, according to a common metric based on economic theory and empirical observation. Impacts are 'converted' into economic terms through the use of valuation functions that indicate the economic value of one unit of the impact. These valuation functions are usually linear. Examples of valuation functions are given in Refs [3–7, 9–15, 17, 36, 55]. The methods that economists use to estimate these economic values are summarized in Section 4.3.

The economic valuation of human health effects is contentious to many who are not economists, though widely accepted by economists. Early studies sometimes used the 'human capital' approach for estimating the value of morbidity or mortality. In this approach, the economic value is based on the medical costs of the health condition plus the lost productivity caused by the illness or injury. The medical costs are the in-patient costs, out-patient costs, medical prescription costs and long term care costs. The lost productivity is measured in terms of the earnings that would be equivalent to the lost time from work. This human capital approach is now viewed as an incomplete measure of the full cost of an illness or injury because it omits the value of the reduced quality of life. On the other hand, the WTP paradigm that is used in modern economics encompasses this value.

Probably nothing is more controversial about economic valuation than the idea of converting mortality estimates to economic values. Much of the objection to doing this stems from a misunderstanding of the rationale. The measure used, the 'value of a statistical life', is a measure of the value for a unit increase in the risk of mortality. This value is not the value of life in general, and certainly not of any particular person's life. Rather, it reflects empirical evidence that individuals are willing to incur increased risk of mortality in return for more of other things that they value, and that can be measured in economic terms. For example, if a person knows that by driving a car over 120 km/h his/her risk of a fatal accident is increased, and he/she chooses to do so, then the decision to behave in this way provides data on the fact that the individual places some value on travel time and is willing to make a sacrifice in terms of increasing his/her probability of a fatal accident in return for reduced travel time.

The term 'value of a statistical life' is used in the economics literature, which provides estimates of its magnitude. The value of a statistical life is obviously imprecise. Values are typically around US $4 million — for example, the US part of the US–EC Fuel Cycle Study used a value of $3.5 million (in 1989 dollars) [9]. Other terms can be used instead, such as 'reference value for the protection of lives' or 'economic risk value'. However, these terms still beg the question of how such a value is obtained. In contrast, the term 'value of a statistical life' explicitly reflects the fact that the value is based on aggregate empirical data on the risks that individuals willingly take ex ante, and not on estimates for any specific individual, nor ex post. The ex ante/ex post distinction is important. If a person knows with certainty that he/she is going to die immediately, then this (rational) person would be willing to pay an infinite amount of money to prevent this from happening.

Other distinctions have been made that are similar but not the same. While asking about the 'value of a life' is not considered proper in civilized society, it is considered appropriate to ask or to observe what individuals are prepared to pay to reduce the probability of death. The latter is the essence of the statistical, 'damage based' approach that economists favour. However, individuals' answers to questions may not represent a true willingness. More objective is to ask what society has actually paid to avert a death in various circumstances. This is the question asked in studies by a number of investigators [100, 101]. Cohen [100] showed that this amount varied widely, from a low of \$400 per averted death by immunization in Indonesia to over $\$10^9$ for radioactive waste practices. These studies provide estimates of the costs of controlling pollution, or other sources of risk, and of the 'revealed preferences' of regulators.

There are two schools of thought on the relevance of these studies for estimating the economic value of health and environmental impacts. One perspective is that the 'control cost' and revealed preference approach provides a surrogate measure. According to this perspective, policy makers and regulators are representatives of the individuals who elect or appoint them. Thus, the cost of pollution control and complying with regulations reflects these individuals' preferences and values [40].

The other perspective is that although control cost and revealed preference estimates are useful for evaluating the cost effectiveness of government policies and regulations, they are not estimates of the economic value that individuals place on the risk of mortality. Thus, according to this perspective, the damage based WTP approach is the appropriate one for estimating economic value. Arguments made to support this position are as follows [102]:

- Control costs reflect technological advances, rather than individuals' preferences;
- Whereas health and environmental damages are site specific, control costs are generally not;
- The decisions of policy makers and regulators reflect political negotiation and other factors, rather than purely economic considerations.

Recent studies of the external costs of fuel chains [102] favour this WTP approach.

From an economic efficiency standpoint, a policy or regulation is efficient if its marginal (not average) cost equals its marginal benefit (i.e. the economic value of the expected increase in mortality that is averted as a result of the policy or regulation). The first type of cost can be derived from studies of the kind reported by Cohen [100]

TABLE XVII. SUMMARY OF ECONOMIC VALUATION

Information input	Numerical estimates of impacts
Type of analysis	Use of economic valuation functions based on results in economics literature
Output of analysis	Numerical estimates of economic values of impacts

and Tsengs et al. [101] (though they generally calculate average, rather than marginal, costs). The second type of cost is derived from estimates of individuals' WTP. Thus, one way of thinking about economic values based on WTP in comparison with the costs of complying with regulations is that they are on opposite ends of a see-saw.

A summary of Section 4.2 is presented in Table XVII.

4.3. METHODS FOR MONETIZATION OF ENVIRONMENTAL EFFECTS[12]

A variety of monetization techniques can be used to assign monetary values to environmental effects (damages and benefits) of electricity production. Examples of monetary valuation of electricity related environmental effects are the economic value of crop losses associated with atmospheric ozone levels and the economic value of damage to buildings associated with sulphur emissions.

There are two basic categories of monetization methods:

- Damage based valuation
- Control cost valuation.

The US Office of Technology Assessment [47] has published a background paper which provides a good discussion of monetization techniques. The techniques in each of these categories are described below.

4.3.1. Damage based techniques

The damage based valuation approach uses the WTP concept, which is central to modern economic theory. An important characteristic of the approach is that it is based on the estimated damages to human health and the environment, and not on the costs of controlling the responsible emissions (Ref. [40] describes the latter approach). This approach was used by most of the seven states in the USA that recently required regulated electrical utilities to consider quantitative externality values in their integrated resource planning. These regulations were established before the spate of studies done in Europe [2–7] and North America [8–21] established the damage function approach as being feasible and practical, thus

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[12] Compiled from Refs [21, 47, 103].

TABLE XVIII. SELECTED METHODS FOR ESTIMATION OF EXTERNAL COSTS [104]

Type	Method	Implicit market	Examples of applications
Stated preferences (direct methods)	Contingent valuation	Interviews	Non-use value of wilderness land
Revealed preferences (indirect methods)	Hedonic pricing	Real estate	Price (WTP) of exposure to noise: estimated using the influence of noise on real estate prices
	Travel cost	Recreational services	Price (WTP) for recreational values: inferred on the basis of estimates of time and money used by households visiting a recreational site and then comparison of sites differing in environmental quality

eliminating the need for control cost estimates as measures of environmental damages (though estimates of control costs are still important for comparing the benefits of pollution abatement or prevention relative to the associated costs).

There are both direct (i.e. market based and CV) and indirect (i.e. hedonic pricing and travel cost) methods. These methods, together with some advantages and disadvantages, are discussed below. Table XVIII [104] provides an overview of selected methods and Table XIX [104] presents some of their advantages and disadvantages.

4.3.1.1. Market price method

The market price method is a direct approach in which existing market data are used to place an economic value on an environmental impact. An example of an application of this method is the use of market price information to value crop losses associated with pollution damages resulting from electricity generation [21]. One of the main advantages of this method is its relative ease of application because of the use of existing market data. However, a disadvantage of the market price method is that it is appropriate only for items traded in markets. There are limitations in applying this method to valuation of environmental impacts associated with electricity production because not all of the environmental effects are traded in markets [47]. For example, individuals may place a high value on the preservation of

TABLE XIX. ADVANTAGES AND DISADVANTAGES OF SELECTED DAMAGE COSTING METHODS [104]

Method	Advantages	Disadvantages
Contingent valuation	Directed against specific pollution situation without inference of other issues. Option value can be revealed	Deals with hypothetical situations. Five major sources of biased results: — Difference between WTP and WTA. — Incentive to misrepresent values (non-obligational nature of questioning). — Implied value cues: these biases occur when elements of the contingent market are treated by respondents as providing information about the ‘correct’ value of the good. — Embedding effects: these may arise if the expressed WTP for the given good depends on whether it is valued on its own or as a part of a larger composite good. — Mis-specification of scenario: biases may occur when a respondent does not respond to the correct contingent scenario
Hedonic pricing	Wide experience in economic literature. It concerns values observed in markets	Its theoretical assumptions are not very realistic. Only the use value can be measured. It is difficult to separate the different factors affecting the price of a given commodity. It is not easy to measure the specific influence from noise or from air pollution on housing prices. The option value is not measured. Only externalities that are well perceived (e.g. noise) can be valuated
Travel cost	Appropriate method to value environmental goods	Number of visits made is a discrete variable. Use of continuous estimation techniques is inappropriate. Truncation bias. Surveys cannot take account of those who do not visit the resource. If non-visitors were included in the survey, this would significantly affect the estimate of consumer surplus because of its effect on the specification of the demand relationship

endangered species or a wetland. However, most often these are not traded within the market place, and therefore are not amenable to the use of the market price method for monetization.

4.3.1.2. Contingent valuation method

The CV method is a direct monetization method based on survey techniques whereby individuals are asked in a controlled experiment what they would be willing to pay for improvements in (or willing to accept to tolerate a loss in) environmental quality. Through the use of hypothetical markets, respondents are provided with a starting point bid for a change in environmental quality and are asked whether they would be willing to pay that amount. Alternative bids are introduced, and the process continues until a maximum (minimum) amount is chosen, constituting the individual's maximum WTP (or minimum willingness to accept (WTA)) [47].

Once the survey is completed, statistical analysis is used to estimate monetary values elicited from the sample group. Regression analysis is used, together with socioeconomic data on survey participants, to assess predictors of WTP. The results from the sample group are used to generalize about the WTP or WTA of a larger group, for example all people who would be affected by the construction and operation of a large hydropower plant [47].

One of the main advantages of this method is that because it uses hypothetical markets, it can be used to estimate many more types of externalities. In addition, this method can be used to attempt to place a value on use and non-use value [21].

The major disadvantage of this method is that because it is based on hypothetical situations, there may be significant differences between stated values for improvements in environmental quality and actual WTP for such improvements. In addition, this method can be time consuming and costly to implement [21].

4.3.1.3. Hedonic pricing method

Hedonic pricing is a technique that can be used to measure indirectly the effects of local environmental amenities through examination of real estate values or wage rates. As an example, in the case of real estate values, it would involve the use of statistical modelling to identify property value differentials which can be attributed to specific environmental and other differences between properties. This method, sometimes also referred to as the property value technique, is based on the assumption that the market value of land is directly related to the benefits or 'utility' which can be derived from the property. The values are used as a proxy for individuals' (society's) WTP for an improvement in environmental quality [47]. An advantage of this method is that it has a well developed literature. In addition, it is useful for developing values for aesthetic amenities or property value effects.

One of the limitations of this approach is that in order to develop a meaningful measure of WTP for environmental amenities, all other variables that may affect WTP must be controlled [21]. For example, a study undertaken to develop an estimate of the potential property value impacts which may result from the existence of overhead transmission lines would require that all other variables that could affect property value (size of house, size of yard, etc.) be identified and controlled for in order to establish meaningful WTP estimates.

4.3.1.4. Travel cost method

The travel cost method is an indirect monetization method which uses the economic value of time as the central indicator of WTP. This method has been most frequently used to assess the feasibility of making improvements to recreational sites. When used to assess the value of environmental improvements, environmental amenities are estimated in terms of the costs that individuals are willing to incur to travel to sites to enjoy these amenities. Data are collected in part through the use of surveys and questionnaires. Site data are also required [47].

An advantage of this approach is that there is a wide body of literature on its application. One of the disadvantages is that there are a number of models that can be used to apply the method and this may lead to increased uncertainty if there are significant variations in models.

A combination of valuation techniques is often used for monetizing environmental impacts.

4.3.2. Control cost techniques

4.3.2.1. Control cost valuation

Control cost valuation is a revealed preference method that uses the cost of installing and operating environmental control technologies to meet current regulations as a proxy for the economic value of environmental damages associated with the regulated pollutants. Proponents of this approach argue that the cost of the last unit, or the highest cost of control under existing environmental standards, provides an estimate of society's WTP for a given level of environmental protection and quality. Implicit in this approach is the hypothesis that regulators have assessed the benefits of various levels of environmental quality and have determined the optimal level of regulation on the basis of a comparison of the marginal cost of control against the marginal cost of damage [47].

4.3.2.2. Mitigation cost valuation

Mitigation cost valuation is a revealed preference method similar to control cost valuation. However, the estimates developed are based on estimates of the costs associated with mitigating potential future environmental effects. This technique has been most widely applied to estimate the costs of CO_2 emissions. The US Office of Technology Assessment report [47] cites the use of the mitigation cost valuation approach to assess the cost of tree planting to sequester CO_2 emissions as an estimate of the costs of these emissions.

4.3.3. Discussion

References [21] and [47] contain a discussion of the advantages and disadvantages of the various monetization techniques described above. As discussed in these publications, the most significant limitations of the damage based monetization approach are the potential difficulties in estimation and the uncertainty in estimated costs of impacts for which there are no direct markets. However, the major strength of this approach is that it places an economic value on actual damages to human health and the environment. It also focuses on site specific impacts and, as a result, provides a more realistic and accurate estimate of the costs associated with environmental degradation, information which can be used for the purposes of comparison.

The major advantage of control cost techniques is that cost estimates are relatively simple to calculate. However, their most significant weakness is that the estimates usually bear little relationship to environmental damages that result from electricity generation. In addition, control cost estimates are often estimates for ‘end of pipe’ solutions that focus on emissions only and not on the life cycle [47].

As mentioned in Section 3, environmental damages are usually site specific. Control cost based estimates cannot elucidate site specific issues. For example, pollution control costs are the same for electricity generation options of the same type, regardless of where a plant is located, so that the cost of control for two similar plants would be the same even if one was located close to an urban centre while the other was in a rural area. A more detailed discussion of the control cost approach in comparison with the damage based approach can be found in Ref. [47].

Given that the goal of comparative assessment is to evaluate and compare fuel chains and technologies in order to address risk efficiently, the evaluation must be done on the basis of environmental damage. Environmental cost estimates derived by means of control cost techniques may not be meaningful or useful in a comparative assessment framework.

4.4. VARIATIONS IN ECONOMIC VALUES

4.4.1. Discounting

Some impacts occur once, over a relatively short period, for example during construction of a power plant. Other impacts occur annually, such as health effects from continual discharges during the operation of a coal fired power plant. Still other impacts occur well into the future (e.g. potential impacts of radioactive waste disposal). Comparative impact assessments should use discount rates to adjust future damages and benefits back to current values and then to express these on a 'levellized' basis. The levellized amount is a constant annual damage or benefit which, when summed annually over the lifetime of the power plant in equal amounts, equals the total present value of the damages or benefits from the plant.

The discount rate that most studies use is generally in the range 3–5%. Other things being equal, the social rate of time preference is generally preferred. This is the rate at which society is willing to trade consumption between different periods. It is usually estimated as the rate of return on riskless assets, about 3%. For sensitivity analysis, a range from 0 to 10% is recommended. All of these rates are in real rather than nominal terms, meaning that they are adjusted for inflation.

Some impacts are delayed, such as cancer deaths. A significant time may elapse between the discharge or exposure and the time at which the impact becomes clinically apparent. The approach for dealing with such impacts is to discount the value of the impacts that occur over time with delays, rather than to discount the dose. Thus, according to this approach the value of a cancer case that occurs in the future is less damaging than one that occurs immediately.

Construction impacts and damages are once-only occurrences and do not occur every year during the operation of the power plant. They must be levellized over the lifetime of the power plant. Other capital expenditures should be similarly amortized. These types of damages should also be expressed on a per MW(e)·a or per kW(e)·h basis, as are other types of damages. The general effect of amortizing these damages is that they tend to be smaller than damages that occur each year because the once-only damages are 'spread' over the total number of kilowatt-hours generated over the lifetime of the plant.

For extremely long term impacts, such as those related to long term releases from spent fuel repositories that are part of nuclear fuel chains, and the effects of global climate change in the future that result from current emissions of greenhouse gases, virtually any non-zero discount rate makes these damages almost zero. This issue of intergenerational discounting remains unresolved in the literature. Some analysts suggest that these issues be addressed by means other than the discount rate [105]. Other analysts suggest that the discount rate for intergenerational impacts should be about zero [106]. The reasoning behind this argument is that the cost of the future impact is greater, in real terms, than the current value of the impact. Therefore, the net effect of the escalation and discount rates is about zero. It is advisable that studies use a range of values (e.g. 0–3%) as part of their sensitivity analyses (see also Sections 3.7 and 4.9.4).

4.4.2. Regional variations

4.4.2.1. Site specific effects

The health and environmental effects of fuel chains may vary significantly between regions, even for identical fuel chains. The major factors affecting these differences are:

- — Population size and spatial distribution relative to the source of the discharge,
- — Existence of threatened or endangered species or highly sensitive ecosystems,
- — Local and regional meteorological conditions.

Thus, data on these factors should be collected and used to estimate the impact indicators.

Numerical experimentation has revealed that some types of impacts, such as respiratory damage associated with exposure to ozone, can vary by an order of magnitude, depending on the number of people exposed. Thus, the idea of an ‘average’ or ‘generic’ site for a power plant is problematic, at least for large heterogeneous regions. For some impacts, of course, the source of the pollutants is irrelevant. Specifically, impacts associated with global climate change from greenhouse gas emissions do not depend on where the emissions occur.

A significant complication that arises in the context of a site specific fuel chain analysis is that not all of the activities of a fuel chain are at the same place. For example, the location of a coal mine is different from the location of the power plant (except for ‘captive mines’). Thus, the impacts of coal mining depend on the population and ecosystem exposed near the mine, whereas the effects of emissions from the power plant affect a different population and environment. The regions in which impacts are estimated to occur should be identified. How these regional patterns should be further considered depends on the scope of the study (Section 3.2) and on the planning and policy priorities.

4.4.2.2. Differences in economic values

Regional differences not only affect the nature and magnitude of the impacts of fuel chains, but can affect their economic value as well. The issue is reflected by the question: is the value of a statistical life greater in richer countries than in poorer countries? Similar questions can be asked about the value of other types of impacts, such as damage to ecosystems. The answers to such questions may arise from the context and scope of the study. There are two basic alternative approaches:

(a) Adjust unit values estimated from US or western European data if they are being applied to less developed regions by taking into account the different incomes or individuals' abilities to pay (e.g. by using the ratio of per capita gross domestic products to scale down the USA based values).

(b) Use the same unit values, regardless of where the impacts occur, to reflect an 'equitable' value (e.g. if the analysis is about the global impacts of greenhouse gas emissions from the USA).

For impacts that are local or only to the immediate region around the fuel chain activity, local economic values should be used. For example, local prices should be used for the market values of crops to estimate the impacts on the local region. The justification for using local values for local impacts is that the damages of a power plant are being weighed against its local financial costs (of construction and operation) and benefits (to local businesses and households). In general, values should be used that will be comparable to the costs of averting these damages: the planning or decision making issue is generally to compare averted damages, as valued by the country, to the costs to the plant owner/operator in that country of mitigating those damages by using alternative or additional technologies.

A further complication is that economic values may change over time. Most studies have ignored this. Sensitivity analyses can be used to consider situations in which future impacts are more valuable than current impacts. Real income levels, and thus WTP, will be greater for future generations than for the present generation.

4.5. IDENTIFYING EXTERNALITIES

This section describes the type of analysis required to identify the extent to which estimated damages are in fact externalities. That is, this section focuses on the part of the extended pathway highlighted below:

> Fuel chain activity → Source term → Changes in concentration → Impact → **Valuation → Externality**

Many impact pathways that may lead to sizeable impacts but that are clearly not externalities may be screened out of the analysis in the initial stages of a study (Section 3.2). This section refers to impacts that were not screened out because the extent to which any damages or costs are internalized was uncertain or contentious.

4.5.1. Meaning of externalities

Externalities are effects on the well-being or profits of third parties that are not taken into account in the market by the producers and consumers of a good or service. There are distinctions between externalities and pollutant emissions, pollutant concentrations, impacts and damages. In fact, they follow a logical order. Interpreted broadly, emissions from a power plant or from some other source in the fuel chain include any residual effect such as noise, the existence of a power plant where there was none before, or change in erosion (as a result of change in land use). Many emitted pollutants undergo chemical reactions or are dispersed from the source of the emission to neighbouring areas. This dispersion changes the concentrations of pollutants relative to their levels without the fuel chain activity. Populations, ecosystems and infrastructure (such as buildings and roads) that become exposed to these changes in pollutant levels may be at greater risk of certain damaging impacts. These impacts can, in many cases, be expressed in economic terms. When expressed in economic terms, these are the damages associated with the impacts. In some cases, the damages are not reflected in the market for electrical power or for the fuel. Such damages are external costs. A portion of damages is externalities. That portion is some fractional number between 0 and 1, depending on the extent to which market, insurance and regulatory conditions explicitly account for the damages.

In defining impact pathways, analysts should keep these distinctions in mind. The reasons for making the distinctions are that they facilitate: (a) defining the logical sequence of impact pathways; and (b) making comparisons of different types of impacts or of damages or externalities. Table XX gives examples of impact pathways, making the distinction between emissions or discharges, changes in concentration, impacts, damages and externalities. For example, CO_2 is not an impact of fossil fuel use. It is an emission. The impacts are what result from global climate change — changes in ecosystems, effects on coastal areas, and possible changes in morbidity and mortality due to effects on agricultural production. In the nomenclature used in this report, global climate change per se is not an impact. The impacts are the effects of climate change on human health and the environment. These are the things that individuals value. The economic value of these impacts is the damages (or benefits) of the CO_2 emissions.

4.5.2. Estimating externalities

The final step in the impact pathway approach is to discern the portion of the estimated damages that is in fact externalities. Most studies do not explicitly consider this step. However, an underlying motivation for many studies of environmental risks and impacts is to provide information to support policy decision making, to ‘correct’

TABLE XX. EXAMPLES TO ILLUSTRATE DISTINCTIONS BETWEEN EMISSIONS/DISCHARGES, CHANGES IN CONCENTRATION, IMPACTS, DAMAGES AND EXTERNALITIES

Emission or discharge	Change in concentration	Impact	Damages	Externality
CO_2	Increased concentration of CO_2 in atmosphere	Estimates are imprecise but impacts are thought to include changes in coastal ecosystems and in built environment, changes in agriculture production, and possible starvation due to increased frequency of floods and droughts	Economic value of impacts	In most countries, none of the damages are internalized; thus, all of the damages are externalities
SO_2	Formation and dispersion of sulphates, for example	Increased risk of morbidity and mortality from respiratory problems due to inhalation of sulphates	Economic value of expected increase in morbidity and mortality. This value includes decreased, or lost, quality of life, not just medical costs and lost wages or productivity	In regions without internalization of these damages, the externality equals the damages. In the USA, with trading of SO_2 emission permits, an indeterminate portion of the damages is internalized
Radionuclides (in the event of a nuclear power plant accident)	Increases in radionuclide concentrations for thousands of kilometres	Increased risk of morbidity and mortality from certain cancers	Economic value of expected increase in cancers	In the USA, a portion of the damages is internalized through the Price–Anderson Act

TABLE XX. (cont.)

Emission or discharge	Change in concentration	Impact	Damages	Externality
Noise from wind turbines	Increase in noise levels at locations near wind farm	Undesirable effects on auditory senses	Willingness of individuals to pay to avoid noise, e.g. through real estate prices of land near wind farm	All of these damages are externalities because there is no market mechanism that internalizes them
Reduced flow of waterfall caused by dam	Reduced flow of waterfall caused by dam	Reduced visual aesthetics of waterfall	Economic value of reduced aesthetics, e.g. as estimated in a contingent valuation study of individuals' willingness to pay	None of the damages are internalized; thus, all of the damages are externalities

for market imperfections. In this case, analysis of externalities is indeed important. Some environmental damages are already internalized and reflected in energy market prices through government regulations, special taxes, private insurance, and wage premiums to compensate for occupational risks.

The estimates of damages (or benefits) should serve as a starting point for determining what portion of these damages is in fact externalities. However, there is no simple mathematical formula for estimating externalities as a function of the damages. Rather, it is necessary to assess each impact pathway individually.

In carrying out this assessment, analysts must ask whether there are any market, fiscal or regulatory conditions that explicitly account for the damages in such a way that their value is reflected in market prices. Specifically, the analysis should consider each of the possibilities listed in Table XXI. This table lists factors that could be used to internalize some of the damages and gives examples of their use. The amount that is not internalized remains as an externality. Even if all externalities were to be eliminated, some damages would generally remain. According to the principle of economic efficiency, it is quite all right, and in fact optimal, that these damages exist. The fuel and electrical power markets reflect the economic value of these damages. It

TABLE XXI. WAYS IN WHICH DAMAGES CAN BE INTERNALIZED

Nature of impact and damage	Way in which damages are internalized	Examples
Occupational injury, including long term health effects	Wages and health insurance	Some portion of the increased risks of mining is internalized in higher wages and in medical insurance benefits provided by employers, who then pass these added costs to the buyer of the fuel
Damage to aquatic life from mine runoff	Regulations that set standards on allowable discharges	Many countries have water regulations. However, these regulations may over- or under-regulate from an efficiency standpoint. Also, if there is non-compliance, externalities could occur
Human health effects from air pollution	Regulations on discharges and/or on maximum local concentrations	National Ambient Air Quality Standards in the USA and similar regulations in many other countries. These regulations reduce the externalities. However, standards are no easy solution for eliminating externalities [8, 10]
Effects of global climate change due to CO_2	Taxes	Norway, for example, has carbon taxes
Damage from oil spills	Payments or fines	In the USA, the Oil Pollution Act requires the responsible party to pay the cost of an oil spill. In the case of a small oil spill, the responsible party may not be known, so the damages would not be internalized
Effects of nuclear power plant accident	Insurance requirements	In the USA, the Price–Anderson Act requires utilities to carry insurance that covers them, to a limit, in the event of a nuclear power plant accident
Ecological and human health effects from SO_2 emissions	Tradable emission permits	In the USA, there is trading of SO_2 emission permits. Also, there is trading of NO_x emission permits in southern California. Trading does not completely internalize externalities because their magnitude depends on the location of the emissions and the affected environment and population. Also, emission caps are not always set at their most efficient level
All types	‘Voluntary’ installation of pollution abatement equipment	Many electrical utilities install scrubbers, electrostatic precipitators, etc. Plant operators may not voluntarily install pollution abatement equipment because it increases their costs. Alternatively, they may install equipment as a hedge against future, more stringent regulations

would be more expensive to reduce them than to pay for them through the price of electricity.

References [8–15] provide examples of how to estimate externalities and specifically of how to quantify the differences between damages and externalities. However, even these reports devote considerably more attention to estimating damages than externalities.

A good example of the complexity of the issue is found in coal mining. In many countries, miners have wages that are high compared with those of others in the labour force with comparable skills and education. However, the wage premiums to miners are to compensate them for the occupational risks, both short and long term. Thus, some analysts argue that damages associated with the health risks in coal mining are internalized, being reflected in wages and thus in the price of coal and electricity. However, some people would also argue that coal miners participate in an imperfect labour market in that they are not perfectly mobile and have imperfect information about the risks. To that extent, some of the damages are not internalized and remain as externalities.

As another example, noise and aesthetic impacts are localized and highly site dependent. Although the amount of noise generated depends more on the project, e.g. the number and type of wind turbines, the impact of this noise depends very much on the location and size of the population subject to the noise. For new installations, the damages from this impact can and should be internalized during the permitting or authorization process by negotiation between the affected population and the plant operator. However, in practice it may not be possible to internalize all of these damages, and some portion may remain as externalities.

A summary of Section 4.5 is presented in Table XXII.

TABLE XXII. SUMMARY OF IDENTIFICATION OF EXTERNALITIES

Information input	Description of impact and how it occurs Numerical estimates of economic damages, if calculated
Type of analysis	Identification of factors that internalize some or all of the damages, e.g. government regulations, insurance, trading of emission permits, wage premiums for high risk occupations, and other market factors
Output of analysis	Qualitative and quantitative estimates of nature and size of externalities

4.6. COMPARISON OF MONETIZED, QUANTITATIVE AND QUALITATIVE DATA

As discussed previously, if it is within the scope of a study, then it is useful to monetize environmental impacts. However, it is not always possible, or appropriate, to monetize all effects, as there are frequently scientific and economic data limitations. Therefore, it is important to recognize that not all environmental impacts can be translated into a monetary unit for the purposes of comparison. For example, it is extremely difficult to estimate the economic value of damages associated with CO_2 emissions because there is no clear scientific agreement on future changes in climate and on their environmental impacts. As a result, the potential implications associated with greenhouse gas emissions are usually described qualitatively, with the level of emission being used as the indicator of the environmental effects. In addition, estimates of the economic value of ecological impacts, for the most part, have not yet been developed. There are many reasons for the difficulty associated with monetizing the full range of environmental costs related to electricity generation options, including the following:

- For some environmental effects, such as ecological impacts, there often does not exist a market where they are bought and sold.
- In some cases, there is still much scientific uncertainty regarding the level of potential damages associated with some activities having impacts, such as CO_2 emissions [107].

However, even those impacts that cannot be, or have not yet been, monetized (and often not even quantified in physical units of environmental impacts) should be included as central elements in comparative assessments if the assessments are to be consistent and defensible.

The real goal of comparative assessment should be to undertake comparisons of risk by gaining a better understanding of the environmental implications of various energy options in terms of actual positive and negative effects. Thus, there is a requirement to consider more than just those environmental impacts that are amenable to economic valuation. There is a need for a method which can assist in the systematic evaluation and comparison of impacts according to multiple criteria which are sometimes measured on different and/or non-commensurable scales.

Therefore, it is recommended that the impact pathway approach (including monetization to the extent that it can be done) be used in conjunction with an approach called multicriteria analysis to facilitate a comprehensive evaluation and comparison of impacts. Hobbs and Meier [108] provide a good discussion on complementary uses of multicriteria assessment and monetization techniques.

4.7. MULTICRITERIA ANALYSIS[13]

4.7.1. Purpose in using multicriteria analysis as part of overall approach

Multicriteria analysis (MCA) is a tool that facilitates comprehensive and consistent consideration, comparison and trade-offs of health and environmental attributes. MCA is designed to assist in the systematic evaluation of options according to multiple criteria which are sometimes different and which may not be measured on an interval (or even ordinal) scale. MCA is not a method that can be used to derive impacts and/or costs, but rather is a method that places different types of impacts on a comparable basis and facilitates comparisons between impacts originally estimated and expressed in different units. In this report, a distinction is made between MCA performed by the analyst, which is comparative impact assessment, and MCA done as part of a decision making or formal planning process, which is multicriteria decision making. The former is part of the overall approach suggested in this report. The latter is beyond the scope of this report.

MCA can be used to compare and assess dissimilar environmental impacts across fuel chain technologies or plans in the absence of a full range of monetized impact information. MCA can also be used to compare and assess environmental and other attributes such as socioeconomic impacts.

The main objectives of MCA are as follows [108]:

- To provide quantitative information where it is difficult to quantify the impacts directly,
- To display risk–benefit trade-offs that exist between different impact indicators,
- To facilitate comparisons and trade-offs of indicators,
- To facilitate understanding of the ‘values’ that analysts place on different attributes.

4.7.2. Steps in multicriteria analysis

Problem structuring

(1) Define the options to be evaluated.
(2) Define criteria (or impact indicators) for comparative assessment of fuel chains or other technology alternatives.
(3) Assess impacts of the options on the basis of evaluation criteria.

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[13] Compiled from Refs [98, 108, 109].

Screening and trade-off assessment

(4) Screen out options that fail to meet minimum standards or are otherwise unlikely to be acceptable.
(5) Develop trade-off curves to improve understanding of the cost of environmental improvement and other trade-offs.
(6) Drop options that are dominated by other alternatives (i.e. options for which there exist other choices that are better by some criteria but no worse by others).

Application of value judgements

(7) Translate impact indicators into value scales (single attribute value functions).
(8) Select a weighting method (or methods). There are a number of different weighting approaches available. Each must be considered in terms of its ease of application, applicability to the particular MCA exercise and the preferences of those involved in the exercise. Analysts (in the MCA exercise) should specify weights on criteria on the basis of their understanding of the relative importance of each of the indicators for each of the options.
(9) Combine weights and rescaled impacts to give tentative rankings of options.
(10) Compare rankings by different stakeholders, negotiate and forward results to the decision making process.

A detailed overview of the steps in conducting MCA can be found in Ref. [98]. The following provides a very brief outline of some of the steps and issues associated with selecting impact indicators, assessing impacts, screening indicators, analysing trade-offs, standardizing impact data, setting weights and amalgamating results. Hobbs and Meier [98, 108] or a similar reference should be consulted if MCA is going to be undertaken.

4.7.3. Selection of impact indicators

Impact indicators are the basis upon which the relative impacts of fuel chain options or plans can be assessed. Caution should be taken to ensure that the indicators are chosen on the basis of:

- *Relevance:* Indicators should reflect the overall objectives of the study and differ between options.
- *Directionality:* Indicators must be defined in a manner that ensures that their magnitude can be assessed and interpreted. This can be accomplished by specifying indicator measurement in terms of maximizing or minimizing, increasing or maintaining, etc.

- *Measurability:* It should be possible to quantitatively measure or estimate directional impacts of each alternative on each indicator, in the unit of measurement that is appropriate for the indicator. Directionality and measurability together determine interpretability, i.e. they permit an interpretation of impacts as being good/bad or better/worse on each indicator.
- *Independence:* Each indicator should be independent of the others, so that double counting, redundancy and repetition can be avoided.
- *Manageability*: In order to ensure independence of indicators, to make assessments comprehensible and to facilitate effective comparison, the number of indicators should not be too large. An excessively large number can lead to difficulties when an attempt is made to place weights on the indicators.

4.7.4. Assessment of impacts

In order to facilitate MCA, it is important to attempt to identify and describe the expected health and environmental impacts using the impact pathway approach and, where possible and appropriate, to quantify and monetize the health and environmental costs to assess damages/benefits.

The impact of each option or plan under consideration should be represented using the units of measurement appropriate for each criterion or attribute. For example, impact indicators could be:

- Measured in units of currency for one criterion (e.g. the economic value of environmental damage, which could include all of the impacts that could be monetized);
- Proportion of area utilized in a region (e.g. as a measure of land use impacts associated with each option);
- Tonnes of emissions (e.g. for CO_2 emissions).

4.7.5. Screening and trade-off assessment

Once impacts have been assessed, indicators which fail to meet minimum standards or are unlikely to be acceptable to decision makers can be screened out. Following this, trade-off curves should be developed to facilitate an improved understanding by decision makers of the cost of environmental improvement and other trade-offs. Then options that are dominated by other alternatives should be dropped. Hobbs and Meier [98] provide a detailed discussion on methods for undertaking trade-off assessment and the usefulness of this type of analysis.

4.7.6. Standardization[14]

Once the impact assessment, screening and trade-off analyses have been undertaken, all of the data must be expressed in a common metric, or ‘standardized’, so that comparisons and assessments can be made of the indicators. For example, impact indicators can be presented on an interval scale (e.g. from 0 to 1). The scale would indicate the relative effect of each fuel chain option being considered on the basis of the relative magnitude of the impact indicator (e.g. CO_2 emissions).

Standardization can be done as follows:

(a) For each indicator, identify the best value (e.g. least amount of crop damage) and the worst value (greatest amount of crop damage) from the alternatives under consideration.
(b) Arrange the impact scale on a horizontal axis from the best value (at the origin on the scale) to the worst value (at the extreme of the scale). The scale will depend on the units of measurement used in the impact assessment for each indicator.
(c) Make the vertical axis, the same for all criteria, range from 0 to 1, representing the standardized values of the impact indicators.
(d) Assign an indicator value of 1 to the best option and 0 to the worst. The other options are located according to their impact values on the line joining the best and worst, and their corresponding standardized values are read off the vertical axis.[15]

4.7.7. Specification of weights

Once the impact indicators (i.e. criteria) are standardized, it is often useful to weight each indicator on the basis of its relative importance, for instance in a comparison of human health and ecological impacts. Alternatively, the indicators could be left unweighted, with the final product of the analysis being a description of trade-offs in either tabular or graphical form. In comparative assessments done by analysts, weights are determined by scientists, engineers and other analysts. If MCA is used as part of the formal planning or decision making process, on the other hand,

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[14] Hobbs and Meier [98] refer to standardization as ‘scaling’. Others use the term ‘normalization’.

[15] If there are thresholds or other non-linear effects, non-linear scales could be used instead.

weights are set by decision makers or their immediate staff, by other individuals or by group consensus. The latter arrangement is usually more appropriate, as weighting represents value judgements rather than technical assessments. Weights would be allocated on a ratio scale, which means that an indicator twice as important as another should have a weight twice the value. In addition, the weights should represent the rate at which a decision maker is willing to trade off one impact with another. For instance, if the weight assigned to aquatic impacts is twice that of terrestrial effects, then an improvement of 0.5 in the former must be just as desirable as an improvement of 1.0 in the latter. Thus, weights should be chosen with respect to the best–worst range of the impacts [98].

It is important to use an approach that encourages users to consider explicitly the trade-offs that must be made when a particular option has to be chosen.

There are a number of methods that can be used to specify indicator weights. The most commonly applied approaches use ‘direct’ methods, in which analysts determine the weights directly [98, 110, 111]. The following weighting methods are commonly used to undertake MCA:

— Point allocation
— Swing weighting
— Trade-off weighting.

4.7.7.1. Point allocation

Point allocation can be done either by distributing 100 points across indicators or by using a ‘hierarchical’ approach in which indicators are categorized. Within the latter approach, weights are placed on the general categories and then distributed among indicators within each category. This method is useful when there is a large number of indicators to consider and can assist in increasing comprehension of the range of impacts.

4.7.7.2. Swing weighting

Under the swing weighting method, the individual or individuals involved in the weighting consider the full list of indicators included in the assessment. The analyst considers an option or plan in which all of the indicators are at their worst level (i.e. greatest amount of crop damage, greatest amount of greenhouse gas emissions, etc.). The analyst then chooses the indicator that he or she would prefer to ‘swing’ from its worst to its best impact value and ranks that indicator as No. 1. This exercise continues until all of the indicators have been ranked by the analyst. The analyst then assigns the first ranked indicator a score of 100. Other indicators are then weighted on the 100 point scale. The second ranked indicator is then weighted in proportion to its importance relative to the first (e.g. 90 points represents 9/10 as important and 20 points represents 2/10 as important). The remaining indicators are then weighted according to their importance relative to the higher ranked indicators. The weighting score should be less than the weighting score of the higher ranked indicator. This process continues until all of the indicators have been so rated.

4.7.7.3. Trade-off weighting

In trade-off weighting, the analyst states how much of one indicator he or she would be willing to give up to obtain a given improvement in another indicator. For instance, one tonne of NO_x might be considered to cause damage equivalent to five tonnes of SO_2. The method then calculates the weights implied by such 'indifference judgements'. Hobbs and Meier [98] provide more detail on this approach.

Most analysts recommend that more than one method be used to gain a better understanding of the trade-offs and comparisons that are being made. If different methods yield different weights or decisions, this is an opportunity for assessors to reflect further on the impacts and their preferences. This has been shown to be helpful in building insight and confidence in the decision makers [112]. Hobbs and Meier [98], von Winterfeldt and Edwards [110] and Clemen [111] provide additional information on weighting issues.

4.7.8. Amalgamation

Amalgamation methods can be viewed as techniques to estimate decision makers' indifference curves. One of the most commonly used amalgamation methods is the weight summation method. This method is used to rank options on the basis of weighting scores and impact values. The weight summation method is most often used to rank plans.

Goal programming is another amalgamation method which can be used to estimate analysts' indifference curves. This method allows for the ranking of plans on the basis of the weighted deviation from a goal or target that analysts would like to see achieved (e.g. a particular level of CO_2 emissions). The less the deviation, the closer to the goal, and thus the higher the plan is ranked.

The next section provides an example of one utility's experience in integrating the impact pathway approach with MCA for assessment and comparison of environmental effects. This assessment is then compared with other planning considerations.

4.8. EXAMPLE OF INTEGRATED APPROACH FOR CONSIDERATION OF ENVIRONMENTAL EFFECTS[16]

Ontario Hydro in Canada is a public utility that provides annually about 134 TW(e)·h of electricity to approximately 4 million customers, either directly or through municipal electrical utilities. In 1994, approximately 62% of the energy produced was from nuclear power plants, 24% from hydroelectric sources, 10% from coal fired plants, about 1% from private gas fired generators, less than 1% from renewable energy technologies (i.e. wind and photovoltaics) and the remainder from purchases from neighbouring utilities.

Ontario Hydro has taken an integrated approach to assessing and comparing environmental effects within its Corporate Integrated Resource Planning (CIRP) process. Ontario Hydro linked the impact pathway approach and MCA in order to evaluate and compare environmental effects associated with alternative plans as part of its CIRP process in 1994–1995. MCA was used in two ways within the process:

(a) To evaluate and compare natural environmental attributes;
(b) To compare environmental and other considerations (cost, reliability, worker health and safety, etc.).

The purpose of the CIRP process was to provide strategic advice to the President and Chief Executive Officer of Ontario Hydro on resource allocation decisions for the 1996 business planning cycle. A range of demand side management and generation supply options were combined into seven different plans and evaluated on the basis of their ability to fulfil the following objectives:

- To provide competitively priced energy services valued by customers;
- To improve environmental performance and make more efficient use of resources;
- To enhance social and economic benefits in Ontario;
- To enhance the financial, operational and human resource viability of Ontario Hydro.

These objectives were used to develop criteria and measures by which the plans were assessed and evaluated.

One of the assessments was an environmental assessment. This was planned to include only the biophysical environment; impacts on human health and the social

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[16] Based on Ref. [109].

environment were considered in separate assessments and were later integrated with other criteria.

The primary indicators established for the environmental assessment were chosen with the objective of minimizing damage to the environment. The measures used were:

- — Incremental land use (ha);
- — Crop damage ($) resulting from ground level ozone;
- — Damage to exteriors of buildings ($) due to acid gas and particulate matter;
- — Acidic deposition (mg/m^2) on sensitive watersheds;
- — Waste generated (Gg by type of waste);
- — Water flow modifications due to new hydroelectric developments (water flow ratio);
- — Impacts of once-through cooling on littoral zones (index based on number, flow, capacity and mode of cooling water systems);
- — Greenhouse gas emissions (Tg and Tg/TW(e)·h);
- — Radioactive waste in storage (Mg);
- — Consumption of non-renewable resources (i.e. coal, uranium, gas, limestone) (Mg).

The assessment was performed on an environmental damage basis, consistent with Ontario Hydro's approach to considering externalities. Impacts were either quantified, and monetized where possible, or described qualitatively, depending on the data available. Additional sustainable energy development considerations were included in the form of 'committed impacts', i.e. impacts that would result from the plans and would have to be managed by future generations (e.g. used nuclear fuel in storage, consumption of non-renewable resources or greenhouse gas emissions). Analysis was performed on a life cycle basis.

Where applicable, environmental damages were assessed and mapped on a provincial watershed basis. Damages mapped were incremental land use, crop damage, building damage and acidic deposition. Although the assessment team was unable to assess directly the impacts of the CIRP plans on the integrity of the watershed ecosystems, information was available on the current state of the watershed ecosystems. Ecosystem information used in the assessment included susceptibility to acidification based on lake buffering capacity and vulnerability to additional land use pressures based on the degree of forest fragmentation as indicated by 'landscape conservation values'.

MCA was used by the five member environmental team to assist in making trade-offs between the ten environmental measures in order to select the most important environmental indicators for evaluating the CIRP plans. The maps of the indicators of ecosystem vulnerability were used together with the maps of environmental damages to assist with this process.

As a result of the damage based assessment and the MCA, four key measures were selected. All are long term sustainability indicators:

- Full fuel cycle greenhouse gas emissions, because of current corporate commitment to reduce these emissions and potential impacts on future generations, and because the impacts are not manageable with current technology;
- Incremental land use, because of risk to habitat loss, degradation and fragmentation, corporate commitment to biodiversity, and the lack of ecological redundancy in southern Ontario;
- Used nuclear fuel in storage, because of its toxicity, the longevity of the problem, potential effects on future generations and the lack of a technological solution;
- Consumption of natural gas, because it is a non-renewable resource in very limited supply and because of the inefficiencies of gas combustion to produce electricity relative to its direct use in heating.

These four measures were then combined with 14 other measures (e.g. financial, socioeconomic and health risk related) to evaluate the seven CIRP plans. MCA was again used to assign 'values' to the measures, to assist in making trade-offs in order to identify the most important components of the plans.

4.9. ISSUES TO CONSIDER WHEN COMPARING INFORMATION

4.9.1. Consistent evaluation

It is important to evaluate impacts consistently across technologies if they are to be compared. The preferred approach for comparative assessment of environmental impacts is to assess the full fuel cycle impacts. This implies the consideration of the more important incremental impacts associated with mining of fuel used to produce electricity, construction of the generation facility, operation of the facility, decommissioning, transportation, and storage and disposal of wastes. In many instances, the level of the decision to be made will dictate the level of detail in the comparative assessment. It is important that if assessments are being undertaken for comparative purposes, then all technologies being considered must be assessed on the basis of the same fuel cycle boundaries and the same temporal and spatial boundaries.

Analysts should be aware that impacts that occur over different time frames or geographical regions may not be directly comparable. For example, impacts that occur now may not be equivalent to identical impacts that occur in the distant future.

Thus, analysts should consider listing estimates in separate geographical and temporal categories (Section 3.6.10). Depending on the scope of the study and on the uncertainties in the estimates of impacts, analysts may also assess whether it is desirable to try to convert these estimates into economic values.

4.9.2. Comparability and transferability of results

Cost estimates are difficult to combine and compare. Many of the external cost studies recently completed involve different technologies, emission rates, populations and other assumptions in the quantification and monetization. Studies use very different methods of estimating, categorizing and reporting results. These methods are so different that in-depth comparison of quantitative results is extremely difficult. In general, only broad comparisons are possible. Resources for the Future, Inc., has done some analyses of the reasons for difficulties in comparing externality values developed in different studies [35].

Monetization methods and results must be applicable to the circumstances of a specific country and utility. This issue of transferability is discussed in Section 5.3.2.

4.9.3. Uncertainty

Identification, quantification and monetization of environmental impacts are subject to a great deal of uncertainty. As mentioned in Section 3, uncertainty is compounded at each step in the methodology. Often, estimated impacts and costs can cover a wide range, depending on the initial assumptions, as is the case, for example, with the wide range of nuclear accident probability figures which currently exist (discussed in more detail in Section 5). Caution should be exercised in providing single numbers as final impact estimates or economic values for the basis of comparison. Single estimates can be misleading with regard to this quality. Uncertainty in all aspects of the methodology, input data and final results must be taken into account so that better decisions are made. Thus, it is important that information on uncertainty be clearly conveyed in the presentation of results. All of the recent external cost studies note that their results contain substantial uncertainty [47]. Section 5.2 discusses sources of uncertainty and ways of estimating it.

4.9.4. Dominance of selected environmental indicators

In many studies, a single category of effects tends to dominate environmental cost estimates. Most of the externality cost studies conducted recently show that human health damages associated with air pollution (usually PM_{10} or SO_2) account for the bulk of the cost estimates ([21] and [47], p. 3). In addition, CO_2 often dominates other pollutants in terms of the possible damages from its emissions.

TABLE XXIII. USES OF INFORMATION ON ENVIRONMENTAL EFFECTS

Planning	Identify levels of demand side management programmes to address societal issues (e.g. greenhouse gas reduction) Evaluate external impacts and costs associated with imports and exports of electricity Compare alternative plans and generation options on the basis of environmental damage
Investment/decision making	Evaluate investment alternatives which reflect consideration of environmental, economic and social factors Contribute to decisions about retiring or rehabilitating existing plants Compare alternative sites and generation options on the basis of environmental damage and other criteria
Selection of environmental protection technologies	Assess the marginal cost of damages in comparison with the marginal cost of control associated with control technologies to aid in decisions about economically efficient control technologies
System dispatch	Assess the environmental implications of the order of dispatch of electricity generation options for the system
Policy making	Develop regional, national and/or international targets and/or policies with the goal of enhancing environmental performance and minimizing environmental degradation Contribute to assessment of optimal reference starting points for emission trading schemes (locally, regionally, nationally and/or internationally, based on potential environmental damages) Evaluate the benefits and costs of new proposed environmental regulations

4.9.5. Data limitations

The lack of data in some cases points to the problem of incorporating potential impacts into the process, particularly when there is no technical means currently available to do a valid assessment. Neither extreme case (a worst case assessment or the omission of any assessment) is really acceptable. For example, in most studies of fossil fuel cycles, the long term health impacts of air pollution are not included because the dose–response functions have not been adequately developed, even though long term impacts in other fuel cycles are included. This is an imbalance that must be highlighted in the decision process and integrated through the use of other mechanisms that will allow for the consideration of dissimilar environmental data.

It is feasible to use qualitative analysis or to use estimates of impacts for which data are available on another jurisdiction with the same technology. There are many sources of information on impacts, such as the recent external cost studies cited in Section 3.

4.10. PRESENTATION OF RESULTS

Presentation of results must be done at three levels:

- Detailed technical explanation of work,
- Summary for decision makers to be able to assimilate easily and use,
- Communication of impact assessment and decision making process to the group affected by the decision.

Detailed transparent presentation of the methodology, assumptions and input data is needed for the first level. Condensation of results is very important for the last two levels. If the presentation of data is too complex, the decision makers cannot use the information and the public will find it difficult to follow (and therefore mistrust the conclusion). It is difficult to summarize a large amount of detailed technical work, but the experience of the ExternE project by the EC has shown that this part of the overall project is not trivial and should be included as an important element of the overall work plan for a comparative impact assessment.

4.11. SITUATIONS IN WHICH INFORMATION ON ENVIRONMENTAL EFFECTS IS USEFUL

Situations in which environmental information can be used include:

- Planning
- Investment/decision making
- Selection of environmental protection technologies
- System dispatch
- Policy making.

These are summarized in Table XXIII.

4.12. INTEGRATION INTO POLICY AND DECISION MAKING PROCESSES

Environmental impacts, once consistently evaluated and integrated into planning and decision making frameworks, can be internalized through a number of different policy mechanisms at the utility, electricity sector, national or international level. The most direct way to internalize environmental considerations is through incorporation of the full costs into the pricing mechanism, often known as full cost pricing. However, this is not normally feasible unless done through direct regulation. Otherwise, it leads to an ‘uneven playing field’, both within the electricity sector and in the broader energy sector. In addition, many analysts argue that full cost pricing is not advisable at this time owing to the level of uncertainty associated with current monetary external cost values, though this remains an issue. The important point is that external environmental impact and cost information can be used to improve the overall efficiency of electrical power decisions.

5. KEY METHODOLOGICAL ISSUES

Sections 3 and 4 discussed briefly a number of key methodological issues. In Section 5, more details and examples are provided to illustrate the complexity of the issues; in a number of cases possible ways of resolving the issues are suggested. However, there is no intention of presenting a complete account of all of the difficulties and limitations encountered in comparative assessment studies. The topics commented on here have been selected with regard to one or more of the following aspects:

- Their potential impact on the required scope and depth of the analysis and, consequently, on the resources needed for the overall effort;
- Their role in the interpretation of the results, particularly in applications that involve decision makers — this may include issues currently considered as controversial;
- Existence of serious gaps in knowledge, unresolved issues and factors causing uncertainty.

In applicable cases the current state of thinking and the drawbacks of the current methods will be discussed. Awareness about the issues summarized here and about the limitations of the approaches used is essential for the analysts as well as for the reviewers and users of the results of comparative studies.

5.1. SETTING BOUNDS FOR THE ASSESSMENT

5.1.1. Fuel cycle definition and scope of assessment

A guiding principle of a comprehensive comparative assessment is to estimate and compare the impacts resulting from the full life cycle of each part of the fuel chain of each energy option being considered. However, an uncompromising, all-inclusive implementation of this principle may result in misallocation of a project's resources. Normally, the focus of an assessment is on a limited spectrum of pollutants and on significant[17] impacts (Sections 3.3.2 and 3.3.3).

Different alternatives can be considered, depending on the objectives of the study:

- Analysis of all stages in the fuel chain (including upstream and downstream parts) versus selected stages;
- Analysis of all phases in the lifetime of each facility (construction, operation, decommissioning) versus selected phases (usually operation);
- Analysis of the full set of emissions and residuals (including indirect[18]) versus direct emissions only.

The experience gained from many published studies (including Refs [2–7] and [8–15]) shows that an a priori focus on only the electricity generating plant is inadequate. The relative importance of the different stages varies greatly, depending on the fuel chain and the type of pollutant. For example, in the case of the fossil fuel chains, there is a clear dominance of greenhouse gas emissions from the operation of the power plants, with significant contributions from gas transport in the gas fuel chain and from mining in the coal fuel chain (methane leakage). On the other hand, in the solar photovoltaic chain, CO_2 emissions are primarily from the processes for material production (particularly the electricity input); the power plant itself is practically free from emissions. Similarly, emissions of actinides and aerosols stem predominantly from either mining and milling or reprocessing in the nuclear fuel chain, while in the coal fuel chain the corresponding emissions originate almost exclusively from the power plant. In the oil fuel chain, non-methane volatile organic compounds (NMVOCs) are primarily emitted as a result of flaring and venting in the

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[17] In this context the impact does not need to be significant in an absolute sense. Also of interest is the relative ranking of the importance of each impact.

[18] Also referred to as secondary, diffuse or grey. This term includes emissions associated with production of materials used for plant construction as well as emissions originating from electricity used as the input to all processes involved in the fuel chain.

extraction step, whereas NO_x and SO_x mainly originate from combustion in the power plant.

The importance of careful consideration of all stages in the different fuel chains may also be illustrated by the statistics on severe accidents. Most of the severe accidents associated with the oil fuel chain occur either during transportation to the refinery or when the oil is regionally distributed. In the case of natural gas the accidents occur predominantly during long distance transportation and in regional or local distribution.

The relative importance of the different contributions is not only fuel chain dependent but also technology dependent. On the basis of current trends, efficiency improvements and technological advances in abatement technologies are expected to reduce many direct emissions from fossil fuelled power plants to very low levels. This is illustrated by an example of NO_x emissions from the coal fuel chain [113]: an advanced coal fuel cycle employing pressurized fluidized bed combustion (PFBC) technology and intended for operation in Switzerland around the year 2020. In this example, 74% of the total emissions are direct NO_x emissions (of which only 19% are from the power plant and 68% are from transport); the remaining 26% are indirect emissions (of which 12% are associated with the electricity mix and 88% with materials). In comparison, the share of direct NO_x emissions has been estimated as 93% for the current coal cycle based on a modern German pulverized coal plant (87% from the plant and 9% from transport); the indirect emissions in this case are only 7% (of which 32% are from the mix and 68% from materials). Details concerning other energy chains and technologies may be found in Ref. [114].

The examples above illustrate the potential consequences of limitation of scope on different levels of the assessment process. Notably only a few studies include indirect emissions.

In the context of impacts, indirect emissions, which occur at many geographically different locations under a variety of conditions, are practically impossible to analyse by means of the impact pathway approach. For this reason most current impact studies normally ignore the associated impacts, with the possible exception of the material intensive chains such as solar and wind. Alternative ways to treat impacts are offered by advances in the life cycle assessment (LCA) approach. In this approach, pollutants can be aggregated into, for example, 13 environmental impact classes such as greenhouse effect, ozone depletion, acidification, photosmog, nitrification and radioactivity [115, 116]. Impact analysis based on LCA is subject to considerable simplifications and the results exhibit the corresponding limitations [113]. The LCA approach usually does not distinguish between the physical characteristics of the emissions (e.g. rate, duration and location), meteorological and topographical conditions, or complex pollutant interactions and transformations. Consequently, for some categories such as photosmog the results are subject to large uncertainties owing to the dependences and non-linearities involved. For other impact classes, LCA based impact estimation may represent a more valid and resource saving approach that could supplement the impact pathway approach (see also Section 5.3).

While it is recommended that in principle no artificial limits be imposed, for practical reasons limits must be drawn. In most comparative studies to date, the boundaries have been set to include the most important impacts that would result from the full fuel chain.

Prior to the evaluation of a given energy option, a review should be conducted to assess qualitatively the potential sources of major health and environmental impacts. Quantitative analysis could be limited to potentially significant pathways (Section 3.3.3). Thus, the importance of power plant construction to the overall fuel chain is not likely to be large if the operation of parts of the fuel chain involves considerable emissions and waste production. If the construction of a facility involves production of raw or specialized materials significant with respect to the background levels of such activities within the region of concern, then inclusion of this stage of the fuel chain is essential. This means that, at a minimum, the construction and manufacturing aspects of renewable energy technologies should generally be studied.

In addition to the construction of the power plant, there are other possible sources of emissions, such as during the transportation of the fuel. Depending on where fuel and other supplies are transported from, these emissions may be as great as those from the operation of the power plant itself.

In general, in fossil fuel chains, the indirect or secondary emissions are between one and two orders of magnitude less than those from the operation of the power plant itself. For advanced technologies, with lower emissions from the plant, the indirect or secondary emissions could be one order of magnitude less.

The situation is rather different with nuclear and with renewable energy fuel chains. On a relative basis, compared with other emissions within a given fuel chain, secondary emissions are generally dominant for the non-fossil fuel chains. On an absolute basis, and comparing between fuel chains, their secondary emissions are less important — generally one to two orders of magnitude less than the primary emissions from a fossil fuelled plant, on a per kW(e)·h basis, over the lifetime of the plant. In general, the credibility and consistency of any study call for a careful and well supported account of the reasons for excluding from quantitative analysis parts of fuel chains, such as secondary emissions, and/or parts of specific life phases of the facilities involved.

5.1.2. Geographical boundaries

The geographical boundaries of the assessment will depend on who is performing the analysis, and why, and what particular impacts are of concern (see

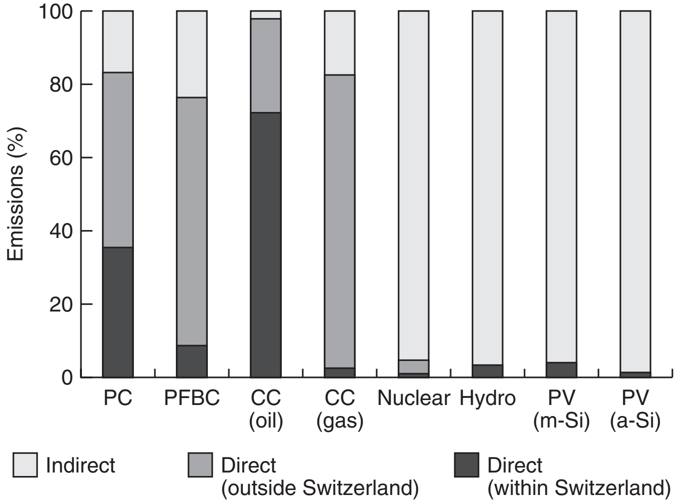

FIG. 5. Direct and indirect SO_x *emissions from selected future systems [114]. (PC: pulverized coal combustion plant; PFBC: pressurized fluidized bed combustion plant; CC: combined cycle plant; Nuclear: advanced designs, AP600 and ABWR; PV (m-Si): photovoltaic roof panels with monocrystalline silicon; PV (a-Si): photovoltaic roof panels with amorphous silicon.)*

also Section 3.2). The definition of the fuel chain, as discussed in Section 5.1.1, embraces various geographically distributed stages. Few countries have a full fuel chain within their borders and the emissions associated with fuel chain activities outside a particular country may in some cases be greater than the direct emissions within the country where the plant is operated. This is illustrated by Fig. 5 [114], where the total[19] SO_x emissions associated with some selected future electricity supply systems of interest for Switzerland are disaggregated into direct emissions within and outside Switzerland and indirect emissions.

Impacts can be categorized into local (typically <100 km), regional (100–1000 km) and global (>1000 km). The exact boundaries are somewhat arbitrary (Section 3.6.10). Whether all such impacts need to be considered in a comparative assessment depends on the objective of the assessment and on the role that the

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[19] This covers both direct and indirect emissions from all stages of the various fuel chains.

assessment is envisaged to play in any related decision making process (Section 3.2.1).

A crucial modelling question is how far from the source it is necessary to follow the pollutants in order to capture all impacts which significantly contribute to the overall result. Some air pollutants are transported over thousands of kilometres. On the basis of a simple dispersion model it has been shown for particulates, SO_2 and NO_2 that accounting for the total impact requires the range of the analysis to be extended beyond 1000 km (Fig. 4 [71]). This conclusion has been confirmed by comparison with EMEP results [69].

It is recommended that the geographical boundaries of the study be defined at the outset. The choice of boundaries should take into account the concerns and jurisdiction of the body making the decisions, the constraints of the modelling tools and the input data available. Risks and benefits due to parts of the fuel chain (e.g. mining) that take place outside the area of the main activity of interest may reasonably be ignored, if justified by the scope of the study, on the grounds that these activities are carried out under the control of and at the discretion of other jurisdictions. For this reason it is recommended that the results be given separately for each fuel chain activity considered. This allows for the use of the results by separate category or as aggregated numbers; in this way the user has the opportunity to utilize the most appropriate results for the decision to be made.

If an international body were performing the assessment, it would seem appropriate that all local, regional and global impacts be considered. Some countries consider it necessary to include impacts which are potentially global or regional in nature (e.g. CO_2 or acidification) in national assessments, even though the impacts are manifested outside their borders. In the case of developing countries, an important consideration is whether, given urgent social needs for electrical power, it is economically reasonable to be concerned about ‘speculative’ global impacts. This issue would have to be addressed by the designers and users of the comparative assessment.

5.1.3. Temporal boundaries

The temporal dimension must be established with respect to various aspects of the comparative study (Section 3.6.10):

- Time horizon, i.e. whether the analysis is about the current situation or about scenarios for the future;
- Operating lifetime of the technologies of interest;
- Time profile of the impacts;
- Time frame for the damage to take place.

The setting of temporal boundaries can have a strong influence on various parts of the analysis and introduces a number of questions:

- Which fuel cycles and technologies are representative for the purpose of the analysis?
- Are the input data available for the period to be analysed?
- At what point do the modelling assumptions lose validity? How far into the future are the defined systems and other boundary conditions applicable?
- Over what period are the impacts to be integrated?

When choosing data for a fuel chain at a point in time, it becomes necessary to ensure that the data are representative of those being considered by the decision makers and that the data used for the evaluation are applicable. This is especially the case when statistical data are used. For example, in the context of accidents there are temporal changes related to advances in technology, regulatory initiatives promoting accident prevention and mitigation, increased hazard awareness, improvements in efficiency of emergency services, etc. Consequently, data representing events that occurred a long time ago are probably not relevant for modern facilities that operate more efficiently, with fewer accidents and less discharges, and under greater regulation. As far as possible, only data representative of current technology and safety practices should be used if the assessments are of current technologies. For future energy alternatives, these data may have to be revised to reflect new advances (see also Section 3.6.11).

Energy supply technologies have an operating lifetime of many years, with environmental consequences over an even longer period. The impacts may be distributed unevenly over time, with some of them concentrated at the beginning or at the end of the operating life of the technology (i.e. construction and decommissioning). For the operation of the technology it has been recommended that a lifetime approach be taken, with a separate reporting of the contributions from construction and decommissioning [2–7].

Some of the impacts may be manifested a long time after the power plant has been decommissioned. Thus, the inclusion of contributions from emissions of long lived radionuclides (e.g. ^{14}C and ^{129}I) or from the long term effects of waste disposal requires integration periods of the order of tens of thousands of years. This presents problems in designing a good assessment methodology and in properly weighting the results for use in the comparison step (Section 4). In the case of high level radioactive waste, models using a wide range of assumptions exist, so an assessment can be made with rather large uncertainty. There is a large spectrum of possible release scenarios in terms of times and quantities. Models are available for estimating the potential future impacts associated with disposal of wastes containing radioactive and/or non-radioactive substances. However, unlike the case of radioactive wastes from the

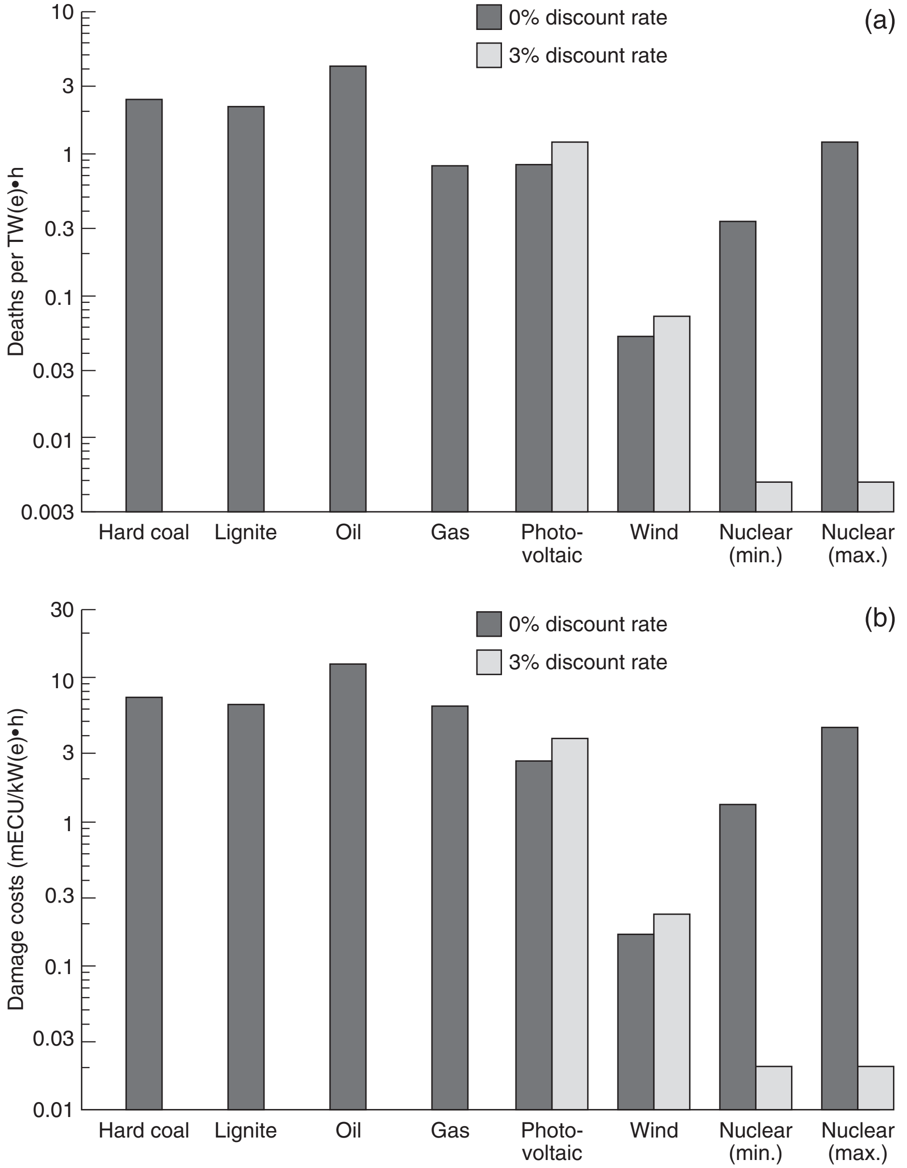

FIG. 6. Public mortality and morbidity risks for two discount rates [70]. The 3% rate is effective for nuclear but has no significant impact on other fuel chains. The numerical values are used to illustrate the effects of discounting on estimates of overall impacts and reflect certain technological and locational scenarios for the power projects (the values are not necessarily recommended as general estimates of public mortality). (Nuclear (min.): complete sealing of abandoned mill tailings; Nuclear (max.): 10 000 year release of ^{222}*Rn from mill tailings.)*

nuclear fuel chain, it is often not required to assess the potential impacts of a given disposal facility for wastes arising from non-nuclear fuel chains. This is in spite of the fact that future impacts are possible, especially for wastes containing significant concentrations of toxic substances which do not decay or degrade over time (e.g. As, Hg or Cd) or long lived radionuclides (e.g. ^{226}Ra or ^{238}U).

Assumptions concerning the treatment of long term effects may have a decisive impact on the overall results. It has been shown [70] that public mortality risks associated with nuclear energy are dominated by dose commitment from abandoned mill tailings if a continuous release is assumed and if the associated health impacts are integrated over a period of 10 000 years. On the other hand, the assessed consequences are very small if complete sealing of mill tailings after mill operation is assumed. This example is illustrated by Fig. 6, taken from Ref. [70], where the related matter of discounting of physical impacts is addressed.

As elaborated in Refs [2–7] and [8–15], the temporal aspects introduce limitations which are related partly to the uncertainty about the physical impacts and partly to the difficulty of defining a reference environment in the very distant future. The relevant variables in describing the reference environment include background levels of emissions and other environmental characteristics, as well as socioeconomic variables such as age and composition of the population at risk.

Since the impacts arise far in the future, there is the question of the validity of the lifestyle assumptions that must be made when modelling the impact pathways (e.g. whether people in the distant future will live and eat in the same manner, whether there will be advances in the elimination or treatment of cancer, and what the world population will be). This question can be addressed by clearly presenting the assumptions in the analysis and presenting the results with the uncertainty estimated for the modelling exercise. In this way, users of the data can decide whether uncertain data should have the same weight in the decision process as information that is known with more certainty. Where there is no clear reason to make any other assumption, the present situation should be considered as applicable. Another important question that can influence the weighting or decision making part of the process is the issue of intergenerational equity, which will be addressed in Section 5.2.4.

It is recommended that in defining the scope of the assessment, the temporal boundaries be set with consideration of the questions to be answered and the concerns of the people who will be confronted with the decisions supported by the information generated in a comparative assessment. The temporal boundaries should then be clearly defined and respected within all fuel chain assessments to the extent possible. If the results are reported clearly by time category, as with the geographical boundaries, it will be possible to use the most appropriate information for a given decision process. These issues are discussed further in Section 5.2.3, which considers the use of aggregation of individual doses into population doses, and assessments to be made for the distant future.

5.2. MODELLING AND ANALYTICAL ISSUES

5.2.1. Examples of unresolved issues associated with specific impacts from normal operation

5.2.1.1. Impacts of particulates

Professional understanding of the effects of air pollution is in a state of flux. Thirty years ago, attention was paid to SO_2, NO_2, SO_x, NO_x and O_3. In developed countries, regulations were put in place to control these pollutants and standards are now usually set below an assumed threshold.

However, around 1970 professional perceptions started to change. Experiments suggested that guinea pigs were more sensitive to particulates than to sulphates. Epidemiological associations were larger and more significant when total suspended particulates matter (TSP) was used instead of SO_2 as a surrogate for pollution. Attention focused ten years ago on the fraction of particulates with diameters less than 10 µm (PM_{10}) and more recently on those smaller than 2.5 µm ($PM_{2.5}$) and even less than 1 µm (PM_1). These finer particulates penetrate indoors and are not easily trapped by filters, whether in the power plant stack or in the human nose. They are deposited more slowly out of power plant plumes than larger particles.

There are indications that there is a linear dose response to particulate matter down to ambient concentrations that are common in the eastern USA and in Europe [117]. Schematic models have been developed that might describe such behaviour [118, 119], thereby adding to the plausibility. Nonetheless, the possible existence of a no-threshold effect has not been formally accepted or incorporated into regulations by any government. Some analysts [26, 120] have considered these effects in this way (although they listed them under morbidity); others have not.

The difference between TSP, PM_{10} and PM_1 as indicators is quantitatively important. Hamilton [26] used TSP as an indicator. In the USA and Europe, TSP levels have decreased over the last twenty years, whereas PM_{10} levels have remained relatively constant. PM_1 has not been measured, but levels might be rising. Thus, the coefficient used by Hamilton for air pollution related mortality may underestimate it because a larger fraction of TSP is now what many analysts believe to be the more dangerous PM_1 fraction than for the data he analysed. This effect is general. Whenever a health effect is related to a surrogate for the true cause, the estimate of the calculated impact is different from the situation when the true cause is known. The calculated impact may be less than the true impact.

In view of these complications it is recommended that analysts calculate the impacts of particulate matter with and without a threshold for their effect and for a possible range of thresholds.

5.2.1.2. Potential health effects of power frequency (50/60 Hz) electric and magnetic fields

There have been over one hundred epidemiological studies of a possible effect of electromagnetic fields upon health. Many claim a positive, statistically significant association but none go so far as to attribute causality. There are over one thousand papers and reports on the subject. There are also over seventy reports issued by scientific panels or government bodies, which constitute detailed reviews of the range of electromagnetic field research and literature (see e.g. Refs [121–125]). None conclude that there is an effect against which we must guard.

Nonetheless, there remains considerable public concern, particularly in developed countries, and any decision maker and therefore analyst must be aware of the issue. The magnetic fields that generate the concern are small (0.3 μT or 3 mG), one hundred times smaller than those experienced by passengers on electric railways (driven by alternating current and overhead power), who do not express this concern. The ordinary type of dose response (more is worse, less is better) does not seem to apply, and no one has proposed a definite dose–response relationship. This makes it difficult for any analyst to address the problem, even in the sense of suggesting an ‘upper limit’ to the effect.

Since all electricity is expected to produce this effect on health, if it exists, the effects would be expected to balance each other in comparisons of electricity generators. However, this is only true if one compares centralized power systems. A distributed electricity generation system will obviously have fewer high current transmission lines and fewer problems, whether real or perceived. Also, sparsely populated areas would experience fewer impacts, owing simply to fewer people being exposed.

5.2.2. Severe accidents and risk

5.2.2.1. Importance of severe accidents

Along with the impacts of the normal operation of fuel chain activities, treatment of severe accidents should be an integral part of any comprehensive comparative assessment. At the same time, the topic is controversial, there are serious gaps in knowledge and the purely technical and/or economic perspective on the problem is not considered to be sufficient when the matter is discussed in the context of decision making.

Not all aspects of severe accidents are amenable to quantification. This applies in particular to environmental effects such as loss of quality, aesthetic values, disturbance of the ecosystem or genetic deterioration, irreversible damage and social impacts of a psychological nature. Some of these impacts also arise during normal operation of a power plant, but they are not nearly as severe as with a major accident. In the context of supporting decision making, at least a qualitative accounting for these effects is essential.

On the basis of experience and analyses, it has been found that the potential for severe accidents is concentrated in specific parts of the different fuel chains [126]:

— *Coal cycle:* explosions or fires in underground mines; collapse of roof or walls in underground or surface mines; tailing dam collapse; haulage or vehicular accidents.
— *Oil cycle:* off-shore rig accidents; fires or explosions from leaks or process plant failures; well blow-outs, causing leaks; transportation accidents, resulting in massive environmental damage or in fires and explosions; loss of content in storage farms, resulting in fires or explosions.
— *Natural gas cycle:* same as for oil cycle.
— *Nuclear cycle:* loss of coolant water or reactivity transient and reactor meltdown; accidents during shipment of high level waste.
— *Hydropower cycle:* rupture or overtopping of dam.
— *Geothermal cycle:* well blow-outs, resulting in the release of toxic gases.
— *Biomass cycle:* not identified.
— *Wind cycle:* missiles in densely populated areas.
— *Solar photovoltaic cycle:* release of toxic materials during photocell manufacture.
— *Solar thermal cycle:* release of toxic working fluids.

The accidents usually stem from a combination of design failure and human operator error.

Past experience provides a valuable source of information on accidents. Many databases covering accidents of human and natural origin exist. However, few of the sources explicitly deal with energy related accidents. A recently established comprehensive database on severe accidents [127] focuses on accidents in the energy sector and contains data on over 3300 energy related accidents. Evaluations have been performed for coal, oil, gas, nuclear and hydro power cycles.

Figure 7 [127] shows the estimated number of immediate fatalities, injuries and evacuated persons per unit of energy for six fuel chains; only accidents with at least five fatalities, ten injuries and 200 evacuees have been included. The results are based on worldwide accident records. The completeness of the data is much higher for fatalities than for injuries or evacuations; particularly poor is the information on evacuations associated with hydropower.

Figure 7 shows only immediate fatalities. Delayed fatalities are a separate issue. This leads to the question of the applicability of historical data to the situation being

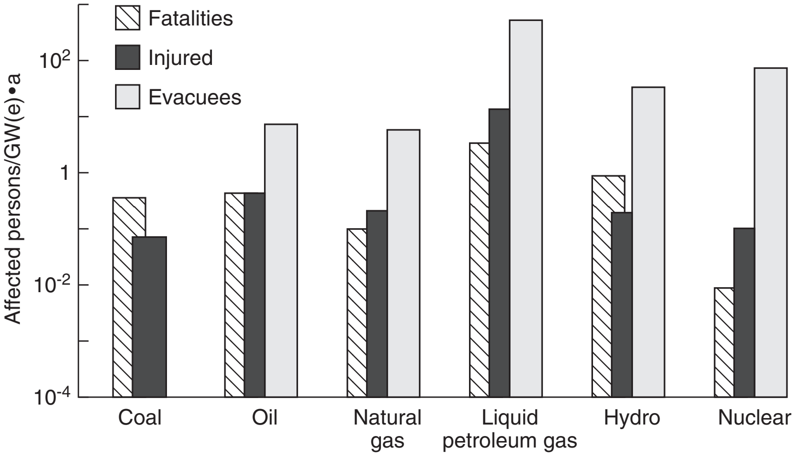

FIG. 7. Comparison of energy related severe accident records for the period 1969–1996: immediate fatalities, injuries and evacuees per GW(e)·a [127].

analysed. Thus, the evidence solely based on accidents that occurred in the past provides only a partial and not always relevant picture of the risks for the following reasons:

- Conditions (e.g. with respect to technology, safety principles and the cultural, physical and operational environment) characteristic of a specific event may be such that its applicability to other conditions may be questionable, and possibly precluded.
- Data on actual experience, if available, in most cases represent only some examples from a wide spectrum of potential accident scenarios.
- For some energy sources and for specific parts of fuel chains the statistical evidence is very poor, which can be seen as a consequence of the reliability of the safety systems.
- The impact of expected advances in technology, including improvements of safety specific features, is not taken into account when only past events are evaluated.

Ideally, a balanced and comprehensive evaluation of severe accident risks associated with systems having extensive built-in safety features calls for the use of predictive approaches employing PSA techniques. Evaluations based on past experience are in any case useful as a supplement to PSA or as a source of information to support PSA and to set the priorities; sometimes they are the only available option owing to the limited number of relevant PSA applications.

The crudity and evident unsuitability of a naive historical approach can be seen by combining the current estimate of the Chernobyl specific delayed fatalities (assumed here to be in the range 9000–33 000)[20] with the accumulated worldwide nuclear electricity production until the end of 1996 of 3685 GW(e)·a, which results in 2.4–9.0 fatalities per GW(e)·a [127]. The crucial assumptions made in this exercise are that the mix of reactors worldwide is similar to that before the Chernobyl accident, and that there is no improvement in Chernobyl type (RBMK) reactors. Even then it only applies to a worldwide average and is not applicable to a different class of reactors in a different country. On the other hand, probabilistic plant specific estimates of the normalized number of latent fatalities are, for most light water reactors, several orders of magnitude smaller than this estimate (typically in the range 0.01–0.1 fatality per GW(e)·a). In addition, important safety improvements have been, and are being, made to RBMK reactors. This difference illustrates the limitations in applying past accident data to cases that are radically different in terms of technology and operational environment.

The importance of careful consideration with regard to design and operational features has also been demonstrated in the case of hydropower [127]. These factors lead to significant differences between the frequencies of major dam failures associated with different types of dam. Furthermore, the frequency–consequence curves for dams in Asia and Africa, on the one hand, and dams in Europe and North and Central America, on the other, exhibit differences, with the latter curves showing lower risks.

The contribution of the possibility of severe accidents to the external costs of power production (particularly by nuclear power plants) is a much debated issue. In fact, on the basis of a number of external cost studies carried out between 1988 and 1994, it was found that the discrepancies between the results are largest when the estimates of the expected costs of nuclear accidents are considered. The values cover a range of some five orders of magnitude. As discussed in Ref. [73], the factors which have the primary influence on the results are the approach used for the estimation of accident frequency, the magnitude of the consequences, the scope of the analysis, the nature of risk integration (in particular, accounting for risk aversion) and the economic parameters used. Extremely high results were obtained in studies which use the Chernobyl plant and accident as representative of all nuclear plants and/or as accounting for risk aversion. Eleven published studies of economic consequences associated with severe nuclear accidents were categorized [73] into one of the three types of analysis used in the context of external cost assessment: ‘top-down’, limited

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[20] This estimate is primarily based on the assessed doses received by the emergency workers and by the public. The upper bound was obtained using no exposure threshold.

‘bottom-up’ and full scope ‘bottom-up’[21]. The full scope bottom-up approach, utilizing modern and comprehensive PSA, is regarded as the state of the art. However, among the published studies only two fully implemented this preferred approach.

5.2.2.2. Estimating risks

Risk estimates when directly based on experience or on PSA provide a technical measure of the level of risk. Thus, in the PSA context, risks are integrated by simple multiplication of consequences of specific magnitudes by the corresponding probabilities; all such terms are then added to obtain the overall risk. However, aversion to the possibility of very high damages/losses can have a substantial influence on the behaviour of individuals. Economists and social scientists emphasize the relevance of risk aversion by pointing to the empirical evidence. For instance, in the context of financial investments, the strategy chosen by individuals is clearly affected by the extent of possible losses and not only by the expectation value of the gains.

The issue of risk aversion is definitely important when discussing the role of nuclear power. Extreme nuclear accidents which could lead to severe land contamination of long duration would also result in social detriment beyond the quantifiable components of health and economic detriment. Some aspects of the societal dimensions related to post-accident situations with large scale and heavy land contamination are discussed in Ref. [128]. Obviously, the currently used engineering economic models do not encompass social detriment. Some analysts view the explicit inclusion of risk aversion in the estimate of the economic consequences of accidents as a compensation (or surrogate) for lack of representation of the social dimension. The exclusion of these aspects from quantitative assessment is a serious but, from a practical point of view, inevitable limitation of current approaches. The use of quantitative estimates of risk aversion as a means of addressing this limitation is not completely adequate.

Some studies account for risk aversion by explicit or implicit allocation of extra weights to events with very large consequences. Aversion is frequently introduced as a power factor, i.e. the damage magnitude is raised to the power of the aversion factor. By definition, aversion factors are greater than 1 and in most published cases do not exceed 2. With an aversion factor of 2, an event causing 10 deaths is valued the same as 100 events with one death each. If aversion exponents in the high range are selected, then the perceived risks clearly overshadow the engineering estimates.

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[21] The impact pathway approach, which constitutes the core of the methodology described in Section 3, if fully implemented, represents the full scope bottom-up approach.

Quantification of risk aversion remains a controversial matter. A complete review of the different approaches to the quantification of risk aversion is beyond the scope of this report. Here the discussion, based on Ref. [127], is predominantly limited to some approaches which have been employed in the context of external cost studies. Thus, aversion has been quantitatively addressed in Refs [49, 129]. For example, in Ref. [49] different functions, including a multiplication factor (as opposed to an exponent) of 300, were used. However, there is no empirical foundation for these functions and factors.

Referring to the 'revealed preference analysis' [130, 131] in Ref. [129], the standard deviation of the damages represents the aversion. As pointed out in Ref. [132], following the spirit of this method, individuals' WTP rather than the collective WTP should be used. Given this correction and employing an empirical 'price for risk' parameter[22], Ref. [132] arrives at a much lower estimate of the external costs associated with the aversion than those estimated in Ref. [129]. The approach assumes that the probability distribution for the monetized losses is symmetrical, which generally does not apply. Another concern is the applicability of parameters that reflect the conditions in financial markets, to quantify the aversion to accidents. A discussion of a number of methodological problems associated with applications of the revealed preference approach to large scale energy risks can be found in Ref. [133].

Recently an approach was proposed by Krupnick et al. [134] which accords with economic theory and aims at estimating the difference between the results based on the 'expert expected damage' (EED) approach and those from the 'expected utility' (EU) approach. The term 'expected utility' is used because individuals are assumed to maximize the expected value of their utility over a state with, and a state without, the accident while accounting for the probability of each state occurring (ex ante approach). In the EED approach one estimates the loss in satisfaction from the consequence of an accident if it occurred with certainty and then multiplies the amount by the probability that the accident will occur ('post ante' approach). The authors show that the ratio between the results based on the EU approach and the EED approach is greater the greater the risk aversion, smaller the smaller the probability of the event and greater the greater the loss if the event occurs. Reliable empirical information is lacking also in this case, particularly with regard to the appropriate utility function and degree of risk aversion.

Although this study considered two definitions of risk as alternatives, it is possibly more reasonable to consider them as being complementary. The traditional estimation of such damages has been based on the expected damages approach, where

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[22] This parameter represents the degree of acceptance of variance (uncertainty) on the part of decision makers. In Ref. [129], two extreme values of this parameter, i.e. 0 (corresponding to risk neutrality) and 1 (corresponding to total aversion), were used.

potential losses if an accident occurs are multiplied by experts' estimates of the probability of such an accident. From an engineering standpoint, these values provide the most scientifically justifiable estimate of the risk.

However, these values do not reflect the risk aversion of the population or the lay assessment of that risk. Insofar as the basis of economic valuation is the WTP of individuals (not experts), an argument can be made that this latter approach is just as 'valid' as the former, but that they measure different things. Krupnick et al. [102] have discussed these issues, though from a standpoint that favours one approach over the other, rather than viewing them as complementary.

Therefore, it is probably most useful in comparative impact assessment to regard the two different approaches as complementary impact pathways, rather than as alternative views of the same thing. To expand on this idea, the risk of severe reactor accidents is considered. In a nuclear fuel chain, the conventional impact pathway consists of:

— Technology characterization from nuclear regulatory commission and other reports which permit calculations of occurrences, their probabilities and the release of different radionuclides:
  → Dispersion of radionuclides;
  → Exposure of humans and property that results in impacts, the estimates of which are based on the scientific literature on dose–response functions;
  → Economic valuation of cancer cases and of property impacts;
  → Consideration of the Price–Anderson Act (for the US context), which internalizes some of the damages.

The second impact pathway may be viewed as:

— Existence of a nuclear power plant (binary measure):
  → Distance of plant from nearby communities;
  → Impressions of risks, defined in broad terms to include the proximity of the plant, perceptions of nuclear accidents and their impacts, dread about such occurrences, and other psychological considerations;
  → Economic valuation of these impressions;
  → Impressions about the expected compensation to third parties, compared with impressions about the damages from the accidents (i.e. impressions of the externalities).

Care should be taken that estimates of the impacts and damages of the two pathways do not overlap. The second type of impact does not involve increased physical risk to human health but rather psychological, stress and quality of life impacts from the perception of risk. The first type of risk can be reduced by engineering design improvement. The second type of risk can be reduced by the public and the industry educating each other about the basis of the public's concerns, and by the industry addressing these concerns.

Examples of low probability, high consequence impact pathways that may be considered in the two ways described above are severe reactor accidents and the long term effects of radioactive waste repositories (both are parts of nuclear fuel chains), dam breaches (in hydropower projects) and catastrophic oil spills (in oil fuel chains).

5.2.2.3. Interpretation of information

The expected types of impacts and their role in policy (e.g. whether they are considered to be externalities) differ between countries. For example, the chance of dam breaches will generally not be pertinent to new hydropower projects in the USA because such projects will involve dam backfits (with no increase in the probability of dam failure) or diversion, rather than new constructions. In many other countries, however, new dam construction would be more likely. In the case of oil fuel chains, in the USA the costs of oil spills, even catastrophic ones, are (in theory) largely internalized through the Oil Pollution Act. Another example of how different impacts are addressed in different countries is in the nuclear fuel chain. The Price–Anderson Act in the USA will internalize damages of $200 million, and possibly up to $7000 million (but most would argue that it would probably still not afford full compensation for all of the costs should a severe reactor accident occur).

Global climate change represents a different type of situation. There is great uncertainty about the damages, should climate change occur, as well as about the likelihood of climate change itself. Compared with many scientists' concerns, public concern seems muted. Thus, lay people's perceptions of the probabilities and risks of global climate change may be less severe than those of most experts.

Thus, the strategy to be applied with respect to the treatment of severe accidents in the context of comparative studies will depend on the overall objectives and the analysis boundaries established in accordance with these objectives (Section 5.1). In an inclusive analysis, accidents associated with parts of a fuel chain outside the borders of the country for which the study is being performed should be included. For a specific country various fuel chains usually have very different structures with respect to their geographical locations. For example, hydropower (which represents a simple cycle) is usually completely domestic, while in the case of nuclear power, for most countries only the power plants and waste storage facilities are within the country, with the other parts located abroad. In the oil fuel chain such accident prone activities as oil extraction and transportation by ship are usually totally external but a proper share of these accidents should be allocated to the domestic power production. The analysis of domestic facilities should be based, if feasible, on PSA techniques and supplemented with historical data. Whenever PSAs for other plants and/or past experience are used the applicability of the results to the situation being examined must be considered. This application oriented screening can lead to reduction of the risks for plants having excellent safety features. In other cases, when these features are worse than average, the plant specific risk should be increased on the basis of careful extrapolation.

The following paragraphs summarize the open issues related to the comparative assessment of severe accidents [127].

(a) *Uneven level of knowledge and limited scope of application of risk analysis.* Few comprehensive PSAs have been performed for energy chains other than nuclear power, although there is a steadily growing number of applications for oil and gas extraction, fuel transportation, refineries, gas storage, etc. Regrettably, such studies are seldom published and made available to potential users. In the context of external cost studies, relatively little attention has been given to severe accidents within energy chains other than nuclear.

(b) *Difficulties in covering a wide range of consequences in a consistent manner.* There is a discrepancy between the wide range of consequence categories covered by the definition of a severe accident[23] and the current possibilities to quantify their extent and associated likelihood for different energy technologies. Typically reported risk measures in PSAs of nuclear energy chains are number of early (acute) fatalities and injuries, number of latent cancer fatalities, total population dose from all pathways, individual risk of death and individual probability of latent cancer fatality, and interdicted and condemned land area. For other energy systems, owing to the scarcity of information, poor statistical evidence and lack of accuracy of historical data, the evaluation of consequences in the context of comparative analysis is currently meaningful only for a few damage categories.

(c) *Uncertainties involved in PSA.* Uncertainty is an inherent feature of probability. While uncertainties are implicitly represented in all analyses, including deterministic analyses, PSA makes them more visible. However, the uncertainty range associated with the results of probabilistic assessment of consequences of nuclear accidents is much larger than that for the outcome of the quantification of accident sequences leading to core damage. The most significant limitations of PSA, which affect the uncertainties, are related to the treatment of human interactions, common cause failures, external events,

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[23] The spectrum of consequences of interest includes fatalities and serious injuries, the number of evacuees, a ban on consumption of locally grown food or drinking water, enforced cleanup of land or water and direct economic losses.

phenomenological aspects of accident progression and source term issues. A review of the current PSA limitations (as well as merits), and of the significant progress that has been made in handling some of them, can be found in Ref. [135].

(d) *Treatment of the distribution of impacts in time and space.* Given the increased uncertainty of long range compared with short range assessments, there is a need to agree on reasonable geographical boundaries that reflect the priorities of decision makers, and on how to treat intergenerational impacts. This issue is also relevant to the impacts of normal operation (Section 5.1.3).

(e) *Applicability and transferability of severe accident data.* The existing data on severe accidents are not homogeneous. This may be due to technological variability, variability from country to country or region to region, temporal changes, differences in definition and categorization of severe accidents, and under-reporting. Any use of generic or plant specific data (available for a plant other than the one being examined) must take into account these differences. This inevitably involves use of engineering judgement.

(f) *Treatment of risk aversion and non-quantifiable social detriments associated with extreme accidents.* No consensus exists with respect to the appropriate methods and data to be used to quantify risk aversion, and whether risk aversion should be included at all in estimates of external costs. There is, on the other hand, wide agreement that risk aversion is an indicator for the acceptability of specific technologies, particularly nuclear. The Chernobyl accident demonstrated that non-radiation-related health disorders and symptoms, such as anxiety, depression and various psychosomatic disorders attributable to mental stress among the population, can be side effects of extreme accidents. Psychosocial effects and breaking of social ties are not amenable to quantification within the currently used approaches but may be of comparable or even greater concern than the direct damages.

From the standpoint of technical experts' assessments, risk is generally defined as the expected value of the probability of an event multiplied by the consequences of its occurrence. From a social theory standpoint, on the other hand, the concept of risk is multidimensional. These dimensions include risk perception (i.e. public perceptions of the probabilities of accidents) and risk aversion (i.e. individuals' aversion to low probability, high consequence events compared with higher probability, lower consequence events that have the same technical risk). Other dimensions include the notion of dread (i.e. individuals' fear of the physical nature of the impact).

In this report, concepts such as risk perception and risk aversion are discussed, both because they are important in the overall scheme of deploying energy technologies, and to make clear their distinction from experts' assessments of risks. Reductions in the latter are achieved through technological advances, while reductions in these other concepts of risk are achieved as a result of individuals (and industry) gaining a better understanding of experts' assessments as well as the nature and causes of individuals' perceptions and beliefs.

5.2.3. Aggregation

There are (at least) two different types of aggregation concern. The first type entails definitional data aggregation issues. The data used for an analysis are usually an aggregated version of the phenomenon under study. This aggregation reduces the precision of any analysis, and possibly its accuracy as well. The second type of aggregation issue arises when the estimated effects are combined in some way (e.g. summed) to summarize results. The problem here is that these effects may have very different characteristics: they may be linear or non-linear, independent or interacting, compensating or not, etc.

The ideal case is to use data that exactly apply to the situation being analysed. However, the analyst is frequently confronted with the problem that such data are not available at all or, when random events are considered, that the statistical evidence is inadequate. This leads to the need to aggregate data originating from different sources or from different conditions. As discussed in Section 5.2.2, the applicability of aggregated data on severe accidents is a matter of concern and a source of major uncertainty. Taking hydropower as an example, questions arise with respect to the relevance of aggregating data over time (severe accident records are available from 1850 onwards), over types of dam (gravity, arch, buttress, earth or rockfill), over purpose (apart from power generation, dams may have other purposes such as irrigation, flood control, water storage, navigation or recreation), or over world regions. Obviously, owing to temporal changes, primarily concerning safety standards, structural reliability and supervision, aggregation which includes accident records from the nineteenth century is flawed (concrete was introduced on a large scale around 1930 as a replacement for the structurally weaker masonry) [127].

The outcome of a comparative study is a set of estimates of risk and other impact indicators, usually standardized to a unit of energy for the purpose of comparing options. Aggregation of results raises two main issues: the calculation and summing of contributions from all stages and indicators for each energy option, which may involve the combination of probabilistic and deterministic components; and the aggregation that occurs when drawing conclusions or making policy decisions. This latter issue was discussed in Section 4.

In general, if sufficient input data are available, then very detailed results provide the user of the study with a clearer view of how the results were calculated and a result that can more easily be applied to a specific situation. However, if data are not specific to the situation at hand, or too general, then their relevance to the study is not so apparent. Therefore, it is recommended that a clear appraisal of the intended use of the study be completed before the degree of aggregation is chosen. However, if the only available input data are aggregated data, then there is no choice, but it must be recognized that the results will have a larger uncertainty than if a more accurate representation of a particular situation had been implemented.

The issue of combining probabilistic and deterministic risks arises primarily with the integration of the results of assessments of severe accidents and of the normal operation of the fuel chain. In general, the treatment of accident risk as a rate obtained from the product of estimated accident frequency and consequence, to be added to and compared against observed or projected impacts from routine emissions and operational incidents, has not achieved general consensus in the field of comparative studies. While recognizing that there is a distinct difference in the nature of these two types of phenomenon, arguments have been made in the context of external cost studies that such an aggregation is fully acceptable, provided that the estimates of accident frequency and consequence are realistic. The alternative would be to create a 'catastrophic event' indicator, in which nuclear accidents, oil spills, global warming and dam failures could be included; this leads, however, to other types of comparison issue.

A particular aggregation problem concerns the situation where the risk to individuals is quite small but where a large number of individuals in space and/or time are affected. In the nuclear fuel cycle, owing to the long half-life of some of the radionuclides, a very large number of people (world population) could be exposed to extremely small doses (uncertain and not necessarily measurable) over a very long time (hundreds of thousands of years). Integration of these doses over time and the exposed population leads to a collective dose which can be large. When this dose is then combined with a linear dose–response function with no threshold for the individual exposure[24], the resulting health effects may become dominant in the assessment.

Precisely the above approach has been applied to the nuclear fuel cycle in all recently published major studies; however, this is a subject of controversy. Firstly, the concept of the collective dose has been introduced in radiation protection and may not be relevant for prediction of health effects due to exposure to extremely small doses. Secondly, at low dose levels the uncertainty of the models increases and there is no clear evidence of resulting radiological health effects. As a result it has been suggested that a 'de minimis' dose level be established[25], under which no damages

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[24] In a more general case, the issue is whether the threshold is above or below the background concentration of the pollutant. In the latter case, any increase entails damage, just as in the zero threshold case.

[25] Inspired by the legal principle 'de minimis non curat lex', or the law takes no account of trifles.

need to be considered. In a recent publication [136], the Health Physics Society in the USA recommends against quantitative estimation of health risk below an individual dose of 5 rem (0.05 Sv) in one year or a lifetime dose of 10 rem (0.1 Sv) in addition to background radiation. Below these doses, according to this report, risk estimates should not be used; expressions of risk should only be qualitative, emphasizing the inability to detect any increased health detriment (i.e. zero health effect is the most likely outcome). Using the above dose limits has clear implications for the use of collective doses. According to Ref. [136],

> “for a population in which all individuals receive lifetime doses of less than 10 rem above background, collective dose is a highly speculative and uncertain measure of risk and should not be quantified for the purposes of estimating population health risks.”

This position is, however, not generally accepted.

In principle, the damage assessment should not overlook small effects on the general population as long as people would be willing to pay to avoid them ([8], p. 2-14). This position is different from that taken in the context of setting pollution standards, where policy decisions that ignore small effects may be fully defensible; in this case the priority is to protect against much more significant effects that occur only at higher ambient levels. At the same time it should be recognized that the results obtained following an aggregation process that does not employ any thresholds are conservative and their meaning may be questioned on practical grounds. One possible way to treat this issue is to provide two sets of results, one based on the full spectrum of doses and one employing a cut-off at the level recommended by the Health Physics Society [136]. Another possibility is to complete the collective risk assessment but to provide a clear indication of the large uncertainty associated with the result and explore the best way to weight it as part of the decision making process.

5.2.4. Valuation and discounting

5.2.4.1. Valuation

It is widely acknowledged that some environmental impacts are difficult to quantify (Section 3.6). In these cases it is tempting, and possibly necessary, to use estimates of emissions as surrogates for impacts. For example, the level of emissions of greenhouse gases is generally used as a surrogate for global warming, whose consequences are very uncertain and for which international agreements have been formulated in terms of reductions in CO_2 emissions.

In most cases, however, this course of action is incomplete. As discussed in Sections 3.6.1 and 5.1.1, there are methods other than the impact pathway approach that are less demanding of a study's resources. These other methods include the critical loads approach and LCA [111, 112] and may be more or less relevant to the study, depending on the type of pollutant. However, the results may be subject to more limitations; and additional, partly uncontrolled uncertainties are introduced.

Beyond the problem of estimating impacts is the issue of economic valuation. Such valuation is frequently desirable (Section 4.2.1) but is often extremely difficult to implement. Only impacts that are readily quantifiable can be expressed in economic terms. In some cases, there is a more fundamental issue about whether impacts can be expressed in any meaningful economic way at all. Many ecologists, for example, question whether it is meaningful to establish an economic value for an ecosystem (Section 4.2.1); and many people are uncomfortable with the concept of the value of a statistical life (Section 4.2.2).

Whether economic valuation is to be included in a comparative assessment depends on its objectives and the intended uses of its results. Obviously, if full cost accounting or internalization of external costs is the ultimate goal, then the impacts should be monetized to the extent justified. Section 4.3 provided an overview of the main approaches for economic valuation. There, it was stressed that there are both advantages and disadvantages associated with each method.

5.2.4.2. Discounting

Given that economic valuation is to be carried out in a comparative assessment, the question arises whether a discount rate should be introduced to achieve intertemporal efficiency, fairness and sustainability (discounting is described in Section 4.4.1). Efficiency, fairness and sustainability are different criteria, however, and the differences may have a bearing on how discounting should be carried out in a comparative assessment.

The concept of discounting, as advanced by economists, is used to take into account the idea that the value of an impact in the future is less than if it were to occur today. Discounting is important in comparative assessments because some fuel chains may have long lasting effects or distant future risks. The results of comparative assessments of alternative electrical energy systems thus depend on how discounting is carried out in the analysis. Figure 6 [70], for example, shows the numerical consequences of using different assumptions for the discount rate, i.e. 0% or 3%. Discounting does not affect the numerical results for the fossil fuel systems because the risk of public mortality generally occurs in the same year in which electricity is produced. Discounting slightly increases risks from solar photovoltaic and wind power systems because health impacts result from pollutants emitted during power plant construction, i.e. before electricity generation, so that there is 'inverse' discounting. This inverse discounting means that deaths that took place in the past are considered of higher value than those that take place at the present[26]. In the case of nuclear energy systems, the quantified risks mainly affect future generations of the population (based on aggregation of small doses and integration over a large population and thousands of years). Consequently, the discounted risk is very small.

The questions of whether and how to discount future impacts arise principally because different criteria are used to answer these questions. The rest of this section discusses issues concerning the use of discount rates in the context of each of three criteria: economic efficiency, fairness to future generations and sustainable development.

(a) Economic efficiency and discounting

The concept of discounting is well established and accepted in the field of economics.[27] Discussions among economists about discounting are not over whether it should be done, but over the appropriate value to use. Section 4.4.1 noted that most economists prefer using the social discount rate, which is about 2–4%. Many cost–benefit studies use higher values, usually 5–7%. For example, the guidelines of the US Office of Management and Budget call for the use of 7%.

Most risk assessors (but not all) accept discounting. For example, Ref. [137] concludes that if people are to value future dangers to their own lives, they will do so at discounted rates. This means that WTP, and therefore the utility of reducing these long term threats, will be lower than for similar present dangers. Not unexpectedly, age is an important factor in determining discount rates: the older the person, the higher the individual discount rate. In practice, however, such distinctions are not employed in comparative assessments.

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[26] As emphasized in Sections 4.2.1 and 4.2.2, 'value' means economic value. The existence of such values is reflected by evidence of individuals' willingness to make trade-offs in their participation in activities of different risks and levels of satisfaction. As such, 'value', as used here, does not have any ethical, moral or philosophical connotation.

[27] There are two arguments put forward in favour of the use of discounting in financial evaluations ([10], pp. 4-15–4-17). These are the time preference argument and the opportunity cost of capital argument. The time preference argument asserts that a dollar spent today leads to immediate satisfaction, and that this is preferred to the same level of satisfaction in the future. The opportunity cost of capital argument asserts that the dollar can be invested today, earn a real return and provide a return of more than a dollar a year from now. Both arguments appear valid and are widely accepted.

Thus, if the criterion is one of intertemporal efficiency, the guidance is that discounting should be used for making efficient comparative assessments. Furthermore, sensitivity analysis is advised, with values in the range 2–7%. Lower and upper bounds of 0 and 10% may be used if deemed of value for the purpose of the comparative assessment; but most economists regard these values as being extreme.

(b) Fairness and discounting

If there is concern about intertemporal fairness, in addition to just economic efficiency, then additional questions arise. Should the risk of premature mortality in the future be given the same value as the risk of premature mortality at present? Does society today agree to spend money on preventive activities to decrease the risks of premature mortality in the future when it could probably save more lives in the current generation? The answers to these questions would be theoretically straightforward from an economic efficiency standpoint. However, issues of fairness invoke more subjective and qualitative concerns, issues of equity and context specific considerations that are more problematic than discounting from a purely economic efficiency standpoint.

One approach to the discounting problem, which could account for concerns about fairness, is to treat predictions of health impacts that occur in the current year equally, to have a separate category of health impacts for the current generation, and to have a third estimate of health impacts for future generations. In this approach, these impacts and their economic values would not be combined into a single present value (this is basically the approach reflected in Table XXV of Appendix I). A separate MCA (as in Section 4.7) could then be used to assist in decision making.

There are different variations of this approach. For example, health impacts in the distant future could be treated in a qualitative manner, or be given less weight, to reflect the greater uncertainties in their estimates.

(c) Sustainability and discounting

As mentioned in Section 1.1, sustainable development is “development which meets the needs of present generations without compromising the ability of future generations to meet their own needs” [1]. Sustainability as a criterion is distinct from efficiency and fairness. A sustainable course of action might be neither economically efficient nor fair (depending on one’s definition), though many analysts would argue that sustainability should include elements of both.

At the risk of oversimplification, one can make a distinction between different views of what sustainability implies. Some analysts view sustainability as meaning that the current generation should use its resources so that future generations will have the resources to have at least the same level of well-being as the current generation. By this reasoning, the impacts on the environment and the specific resources available to future generations are of secondary importance. In contrast, other analysts interpret sustainability to mean that significant, irreversible changes to the environment should be avoided, regardless of cost. Accordingly, the well-being of future generations cannot be separated from their ability to experience and use the same resources that the current generation enjoys.

Following the latter perspective, both the time preference and opportunity cost of capital arguments presented by economists to justify discounting can be criticized. The time preference argument may be attacked for not properly reflecting the interests of future generations, nor even those of today's society when considered as a whole.

From the standpoint of sustainable development, there are some special concerns, particularly with respect to irreversibility and the potential for catastrophic consequences. If a power project will cause the extinction of a species, this can never be reversed and the damage may be insurmountable. If a hydropower project floods lowlands, these can never be restored to their original state. With respect to potentially catastrophic consequences, if a power project could be constructed that would yield near infinite satisfaction to the current generation but had a 2% chance of essentially destroying half the planet, would it be better to proceed with the project even if an economic evaluation showed a positive net present value? From the perspective of sustainable development, issues of this kind remain unresolved.

In Refs [2–7], cost discounting is regarded as "necessary in comparing costs at different points in time" and the following conclusions and recommendations are provided:

(1) No discounting should be applied to the physical impacts before they are monetized. Full profiles of the physical impacts should be reported, to the extent possible, to permit discounting at the level of monetary evaluation.
(2) The arguments against any discounting at all are not valid.
(3) A social time preference rate of about 2–4% is appropriate on the grounds of incorporating a sustainable rate of per capita growth and an acceptable rate of time preference.
(4) Rates of discount based on the opportunity cost of capital would lie at around 5–7% for the EC countries. There are arguments to suggest that these may be too high on social grounds.
(5) The treatment of uncertainty is better dealt with using methods other than modifying the discount rate.
(6) Where irreversible damages are incurred, it is better to allow for these by adjusting the values of future costs and benefits than by employing a lower

discount rate specifically for that project or component (Section 4.4.1). For example, if a future generation deems the extinction of a species, for example our own, to be unacceptable, then the cost is infinite at any discount rate.

(7) For projects where future damage is difficult to value, and where there could be a loss of natural resources with critical environmental functions, a sustainability approach is recommended. This approach implies debiting the activity that is causing the damage with the full cost of repairing it, irrespective of whether the latter is economically justified.

Even with these recommendations on the use of discount rates, there are unresolved issues. An important issue arises when impacts cannot be monetized, or even quantified. In these situations, comparative assessments should avoid relying on arbitrarily aggregated or discounted values. Discounting is an economic concept. If discounting is applied to non-economic phenomena, then this would be using it for something for which it was not intended.

One final issue is the following paradox. The calculated risk from radioactive waste facilities is small if no discounting is used and negligibly small if the risk is discounted. Why then does the problem of radioactive waste loom so large in the conscience of our societies? Some analysts would suggest that this paradox stems from the risk perception and intergenerational discounting issues discussed above and in Section 5.2.2. Analysts must be aware, however, that there is no unequivocal answer to this question.

5.2.5. Uncertainty

The issue of uncertainty was raised in Sections 3.7 and 4.9.3. Two general sources contribute to the uncertainty in model predictions. Firstly, there is often uncertainty in the true values of the model parameters (e.g. the hardware failure rates used in the probabilistic risk analysis). Secondly, there is uncertainty in the structure of the model itself (including uncertainty in the validity of the assumptions underlying the model). The first type of uncertainty is usually referred to as parameter uncertainty while the second type is termed model uncertainty. There is a broad consensus that:

- There are considerable uncertainties in the quantification of health and environmental impacts.
- The results of comparative studies should include these uncertainties to provide a more complete perspective to the decision makers. Failure to deal with uncertainties in an explicit manner can result in decisions that are suboptimal or even erroneous.

The treatment of uncertainties is not a trivial task. Comparative impact assessments rarely include a full consideration of uncertainty. A comprehensive set of recommendations and specific advice concerning this topic may be found in Ref. [138].

All steps in calculating environmental damage involve substantial uncertainties. Determining the effects on ambient conditions from plant emissions typically requires air or water quality modelling. While such models have become more reliable, benefiting from increasing understanding of the complex interactions which determine environmental quality and being aided by ever more powerful computers, their predictive powers are still subject to major limitations. Our ability to measure exposure has also improved, but serious limitations remain. For example, the techniques used to determine human exposure in the major damage based studies completed to date still result in wide variation for most pollutants. Thus, caution is required in interpreting the assumptions and the results of these studies.

The scientific evidence regarding the linkage between exposure and human health remains unclear after many years of research. Evidence on the impacts of two pollutants most suspected of causing adverse health consequences — PM_{10} and ozone — remains incomplete. Although recent epidemiological studies regarding the health effects of some pollutants (including PM_{10}) have produced more consistent results than previous efforts, questions remain regarding whether epidemiological studies actually capture causal relationships. Similarly, the epidemiological evidence regarding ozone impacts on health may not have been adequately quantified. Clinical evidence regarding these pollutants is very difficult to extrapolate to any broad population.

As stated in Ref. [8], exposures, projected environmental concentrations and even accidents can generally be treated as 'knowns', but most other health considerations must be classified as 'unknowns' or 'likely associations'. Likely association describes a correspondence between an exposure and an effect, but uniqueness of the cause–effect relationship cannot be demonstrated. Some concerns related to this issue are worth noting [139]. Firstly, it is important to distinguish between health effects based on extrapolation models and those based on actuarial data. Not to do so would confuse information having a low degree of certainty with information having a high degree of certainty. Secondly, although health and accident statistics register the incidence of injury, illness and mortality, environmental risk assessments are often restricted to premature deaths because it is hard to evaluate the severity of non-lethal effects. At present, not enough is known about the incidence of non-lethal effects caused by many chemical substances emitted from various fuel cycles, so a balanced risk assessment is difficult.

The practical difficulty with the impact pathway or damage function approach is that many of the health effects associated with air pollution are linked to numerous pollutants. For example, there is a general debate on how to distinguish the effects of acid aerosols from those of particulates. Apart from synergistic effects possibly accelerating and aggravating the biological damage, issues that significantly contribute to the complexity and uncertainty in the evaluation of health risk impact are the weighting of time delays of biological damage, the age and sex dependence of the impact of exposure, and the possibility of either a threshold or linearity in dose–effect relationships [140]. Many investigators face problems when attempting to extrapolate biological data to concentrations well below the original value. For example, although precise models of radiological risk are commonly used, the health effects associated with small doses from the nuclear fuel cycle are not known more accurately than those from nitrogen oxides in the atmosphere. Yet, most health risk assessors consider that the radiological risk is known accurately while risk from chemical pollutants is often treated as unknown or absent. Both estimates depend on data taken much out of context from where they were collected and depend on mathematical extrapolation models [8].

In relative terms, the quantitative assessment of environmental impact is an even more difficult task than the assessment of health effects and, consequently, the associated uncertainties are correspondingly larger. By contrast with human health, where impacts relate to relatively straightforward indicators (e.g. mortality and morbidity) for one receptor (i.e. people), environmental impacts arise from highly complex pathways that affect a diverse array of receptors (i.e. ecosystems with their various structures and functions).

The discussion above concentrates on sources of uncertainty that are primarily of a technical or scientific nature. To this group belong such contributors as uncertainties in the emissions of major pollutants, in dispersion models and parameters, in dose–response functions and in economic valuations. Other sources of uncertainty were identified in Refs [2–7]:

- Policy/ethical choice (e.g. concerning intergenerational discount rate, variation in the valuation of human life with age and location, and risk aversion);
- Scenarios for the future (e.g. concerning population density and lifestyles).

The treatment of uncertainties in a comparative study is highly dependent on the quality of data, which may affect the appropriate choice of uncertainty estimation procedure.

5.2.5.1. Data quality

The quality of data available to complete the comparative risk assessment for a range of energy options varies considerably. Generally, the data can be divided into a number of broad categories based on the source of data. The characteristics of each category have important implications for the associated uncertainty and the confidence that can be placed in the use of the results. The categories of data are as follows:

(a) *Empirical data based on recent experience* (e.g. health and environmental effects from plant construction and operation). These data represent the most reliable information in a comparative assessment, in that they are close to reality, although they are likely to be conservative in that they do not reflect continued improvements in safety practices, environmental performance, etc.

(b) *Data extrapolated from empirical information* (e.g. construction of new technologies, or occupational health effects for which data may not be collected routinely). Some assumptions are needed to perform the extrapolation, so the uncertainty is somewhat larger than for type (a).

(c) *Calculated data which rely on models and dose–response functions* (e.g. health effects from emissions). These data are potentially subject to large uncertainties, especially in applications of dose–response functions at very low levels of individual incremental exposure.

(d) *Calculated data compounding the use of data of type (c) with broad simplifying assumptions* (e.g. future effects of waste disposal). These data are highly uncertain and can be considered speculative at best.

The implication of this form of data classification is that the more uncertain and speculative the source of data, the greater the caution that should be employed in decision making processes involving their use. All of the above sources of data involve uncertainty. The degree of numerical uncertainty ranges from factors of 2–3 about the median value to orders of magnitude.

Formal systems for signalling data uncertainty and quality exist (e.g. Ref. [97]) and have been applied to the estimation of the emissions, impacts and damages of fuel cycles [8–15]. Uncertainty refers here to the spread of plausible values for a data entry and the level of confidence placed in a quantitative statement. Quality refers to both the worth of a data entry as a piece of information and the credibility of the theory, data and methods used to generate the entry.

5.2.5.2. Estimation of uncertainty

Generally, there are six important steps that are necessary to produce a quantitative estimate of uncertainty [138]:

- Identify the desired measure of risk (e.g. fatalities/time, years of life lost, average individual risk, maximum individual risk and number of persons above an arbitrary level of ‘unacceptable’ risk).

- Specify one or more ‘risk equations’, i.e. mathematical relationships that express the risk measure in terms of its components.
- Generate an uncertainty distribution for each component.
- Combine the individual distributions into a composite uncertainty distribution (for each risk measure).
- ‘Recalibrate’ the uncertainty distributions. This step may involve ‘tightening’ or ‘broadening’ the distributions to account for dependences among the variables and/or truncating the distributions to exclude extreme values that are physically or logically impossible.
- Summarize the output, highlighting important implications for risk management.

The main difficulty in implementing this systematic approach is to obtain relevant information on the characteristics of the distributions for the different parameters. This process normally involves the use of analogy, the use of statistical inference techniques, the elicitation of expert opinion, or a combination of these. In view of the problems encountered many studies use a range of possible values to select point estimates of study parameters. This approach may produce results similar to those from more complex treatments, in terms of the relative importance of various risk contributors. However, the process is arbitrary. It is not clear which characteristics of the underlying distributions are represented by the ranges.

Another informal procedure is to provide a low, central and high estimate for each parameter, from which an indication of the possible range of risks can be obtained. The significance of the combination of a series of extreme values may be difficult to ascertain and therefore the usefulness of such information is limited in decision making. However, if the low, central and high estimates represent characteristics of a distribution (e.g. corresponding to the 5th percentile, mean or median, and 95th percentile, respectively), then the distributions for each parameter are known and can be propagated through the overall model to produce a composite probability distribution (as in Refs [8–15]).

Whenever the complexity of the model is large (e.g. fault and event trees in PSAs), a computer based method is employed for the propagation of uncertainties. Monte Carlo sampling is usually employed in these PSAs or probabilistic risk analyses. However, as pointed out in Ref. [141] and further developed in Ref. [142], in most cases it suffices to specify geometrical means and geometrical standard deviations. Since the models are essentially multiplicative, the central limit theorem implies that the final result for any impact category has an approximately log-normal distribution. This means that relatively sophisticated software may not be necessary.

For some calculated data requiring use of both unverified models and broad simplifying assumptions, the application of the previously outlined procedure may not be feasible. These data may concern physical phenomena that are not well known and the uncertainty could have the form, “if the phenomenon exists, the risk may be very significant, but it may not exist at all.” In such a situation, it may be preferable to remove the parameter from the risk equation and to deal with the issue as a separate indicator in the analysis, to be considered in a qualitative fashion as part of a comparative assessment (Section 4) or of the decision analysis process. This approach allows other considerations to enter into the evaluations, such as differences between developed and developing countries in the importance given to CO_2 emissions. This approach, though passing the issue to a different forum, avoids the potentially serious misrepresentation of the state of scientific knowledge that might arise if the issue were treated as a risk parameter with large uncertainty bounds.

In other situations, such as where calculated effects are in any event small and rely on the integration of minute incremental risks, it may be preferable to neglect the issue in the final assessment or to give it very low weight.

Model uncertainty is even more difficult to quantify than parameter uncertainty. Some reasons are presented below [143]:

- — Absence of consensus on how to quantify and represent model uncertainty;
- — Lack of a clear-cut distinction between model and parameter uncertainties;
- — Scarcity, or even complete lack, of data to benchmark key models of the impact pathway(s).

The options for explicit representation of modelling uncertainties in risk studies are discussed in Ref. [143]. These options have not yet been applied in comparative studies. Instead, modelling uncertainties are usually treated by sensitivity analyses.

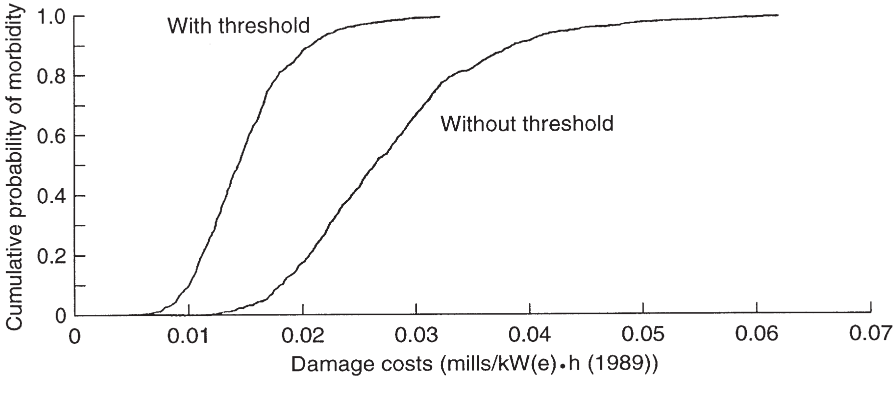

FIG. 8. Sensitivity of health damages to existence of a threshold: particulate morbidity damages within 1600 km of a fossil fuelled plant with and without a 30 μg/m³ threshold.

Figure 8 shows an example of a sensitivity analysis that addresses the issue of the possible existence of a threshold for particulate morbidity impacts.

In summary, it is clear that an indication of uncertainty is important for the valid use of any comparative study. Thus, it is recommended that an attempt be made to present the results with their associated uncertainty estimates. At a minimum the conclusions could be based on point estimates supplemented by the investigation of the sensitivity of decisions to the uncertainties in key parameters. Special issues may call for a treatment outside of the formal uncertainty analysis.

5.3. PRACTICAL AND INHERENT LIMITATIONS

A number of limitations have been mentioned in the preceding subsections of Section 5. Here we focus on the limitations that are of particular importance for the potential users of a comparative study. They are partly practical, i.e. improvements are definitely possible given resources and access to the best available information, and partly inherent, i.e. they are not likely to be fully resolved in the future.

5.3.1. Consistency

Clearly, a guiding principle of any comparative risk analysis process should be a consistent approach in terms of its scope and execution for each energy option. Consistency implies that the same time-scale should be implemented for a given physical impact, irrespective of the fuel chain. Differences may arise legitimately where it is apparent that a particular aspect of the fuel cycle is important for one option but is unimportant and can reasonably be neglected in another. However, it is essential that such decisions be clearly stated and justified in any comparative study.

While striving for consistency is an important principle it must be acknowledged that the current state of understanding of key aspects of comparative assessment is not homogeneous over all fuel chains. Examples of inconsistencies which may make comparisons unbalanced include the following:

- Crop damage studies do not generally look beyond a short period of time and recorded health impacts frequently include only the immediate consequences of any pollutant concentrations. On the other hand, for nuclear accidents the impacts are valued over a very long period. Similarly, while the releases of radionuclides from radioactive waste facilities are considered in the far future, owing to knowledge gaps no long term impacts are accounted for in the analysis of wastes from coal fired power plants.
- Severe accident analysis is often limited to the nuclear fuel cycle, and more specifically to nuclear power plants. Quantitative results are provided for only

a few of the impact indicators. Relatively few applications of quantitative risk assessment exist for fuel cycles other than nuclear, and the information on past accidents is subject to large uncertainties.

- The maturity of analysis in the different fuel chains is not homogeneous. Analysis of fossil fuel, hydropower and nuclear fuel chains can be regarded as relatively mature (this does not exclude possibilities of improvements). Renewable energy sources have potential for extraordinary technological advancements. When comparing future alternatives the question arises of how much credit should be given for rather speculative but not totally unlikely progress (Section 3.6.10).

A clear definition of the assessment, and explanations of the data and the assumptions used, will enhance users' confidence in the results. This can also help to ensure that the results will be used in an appropriate way.

5.3.2. Transferability

The transferability problem arises at two levels:

- Use of basic data which originate from sources other than those directly related to the application being investigated;
- Use of higher level (calculated) results from other studies.

As discussed in Section 5.2.5, the quality of data is highly dependent on their origin and particularly on their specificity for the reference environment. Numerous examples can be given to demonstrate the problems and questions that arise when data and results are directly transferred from one application environment to a totally different one. The following examples illustrate some of the transferability issues:

- Health and environmental damages are highly location specific. This means that they may depend on characteristics that are region specific (e.g. overall environmental quality level), site specific (e.g. baseline level of pollution) or, in some cases, specific to the individual (e.g. age, sex or household size). The degree to which transferability can be credibly carried out depends on the nature of the end point [8].
- In the evaluations of severe nuclear accidents in some earlier studies of external costs, the Chernobyl accident was used as the reference for calculations concerning plants operating in developed countries. Such an approach is associated with a number of fundamental problems [73]. Firstly, one extreme accident that occurred at a plant with a specific (flawed) design, operating in a

specific environment (less developed safety culture) and located at a specific site, is chosen to represent the whole spectrum of hypothetical accidents with varying consequences, or to provide the only reference for some highly questionable extrapolations. Secondly, with this approach, the estimation of the consequences conditional on specific releases is purely deterministic; different weather conditions, accident management strategies, sheltering conditions and evacuation practices are not considered.

- In the case of hydropower, there is great regional variation, with many dams of many different types (e.g. there are 125 large and many more small dams in Switzerland alone), there are both old (over 150 years) and new dams, there have been many accidents, there are no PSAs and there is no international standardization of licensing requirements. Consequently, although one may be able to make statements about the general safety of the dams in a specific region, one cannot make statements regarding the risk that each dam poses individually.
- Should the value of life used in the studies carried out by highly developed countries also be used in the studies carried out by developing countries? Following ethical arguments the answer is probably yes; on the basis of economic arguments the answer is probably no. Consequently, the resolution will depend on the specific objectives of the comparative study (Section 3.2).

The impact pathway approach, being a bottom-up approach, minimizes the transferability problem compared with simpler top-down approaches. Nevertheless, in numerous circumstances there will always be a need to transfer data from other contexts. In the recent major studies of external costs the fully comprehensive plant- and location-specific bottom-up approach has not been applied to nuclear and other accidents [73]. Thus, in the ExternE project [2–7], which analysed the French nuclear cycle, a representative US plant was chosen as the reference, and calculations were carried out for a hypothetical site in Germany; in the US–EC Fuel Cycle Study [8–15], a hypothetical plant was assumed to be located at two hypothetical sites in the USA. In both cases only a few release scenarios were analysed.

Utmost caution should be taken when transferring the calculated external costs from one environment to another since these aggregated results are implicitly highly dependent on numerous basic data and assumptions. Some key factors affecting the magnitude of externalities have been identified:

- Type of technology, type of fuel cycle and the nature of the associated residual effects;
- Quantity of emissions;
- Treatment of global warming;
- Treatment of severe accidents, particularly nuclear;

- Existence of highly valued ecological resources;
- Geographical distribution of population;
- Degree of internalization;
- Background levels of pollutants and atmospheric chemistry;
- Meteorology.

Different studies will, of course, produce different estimates of impacts and external costs. Table XXIV lists the factors that account for most of the differences in the numerical estimates between the earlier top-down and aggregate studies, on the one hand, and the more recent bottom-up studies. (This table includes factors that are not related to health and environmental impacts.) Studies differ markedly in their assumptions and in how they calculate many of the impacts.

This report focuses on the impact pathway approach as a well established methodology for the detailed analysis of health and environmental impacts of electricity generating systems. However, given objectives different than those of the two major external cost studies [2–7, 8–15], limitations of resources, the need to investigate a large number of options and the country specific structure of the various fuel cycles (most countries have only a limited number of stages of the fuel cycles within their borders), the full scope application of this approach as practised in the two major studies may not be the most pragmatic. With respect to the objectives, some countries carry out comparative studies to provide support or input to decisions concerning energy options for the future. Power generation is here considered as a part of the overall energy system, which also includes heating and transportation, and the implementation of the selected options would not be immediate but would take place in, say, 15–30 years. This means that: the technologies of interest are not those currently operating; prospective technological advances should be accounted for; the sites of future plants may not be known (hypothetical sites can be assumed, however); and the scope of the whole undertaking is very large. Clearly, the full scope impact pathway approach is not fully suitable for such applications, especially since its single plant focus [144] is problematic. Accuracy–scope trade-offs in terms of balancing between practicality for resource planning and accuracy of environmental impacts are necessary. Suggested compromises could include combinations of the following [113]:

- Detailed modelling of domestic parts of the energy chains, concentrating on the stages expected to have significant impacts.
- Use of relevant results from the published major studies on externalities (e.g. Refs [2–7] and [8–15]) for the stages of the fuel chain that are outside the country performing the analysis or that are domestic but are expected to contribute insignificantly to the overall results. In view of the transferability problem, this must be subject to appropriate adjustments.

TABLE XXIV. FACTORS ACCOUNTING FOR MOST OF THE DIFFERENCES IN NUMERICAL ESTIMATES BETWEEN TOP-DOWN AND BOTTOM-UP STUDIES

Fuel cycle	Key factors
Coal and oil	General methodology used in the two sets of studies Assumed level of emissions from power plants Effects of sulphate aerosols (greatest source of damage in some studies) Estimated damage to buildings Nature and extent of damage from global climate change
Gas	Level of CO_2 and NO_x emissions Modelling of ozone formation
Hydro	Unique site attributes (e.g. unique ecosystems)
Wind and solar	Avoided pollution (i.e. whether it is credited to renewable energy technologies) Employment benefits (i.e. how they are calculated)
Nuclear	Frequency of severe accidents (i.e. whether Chernobyl type assumptions are used) Estimates of radionuclide releases and population exposure Perception of risks (i.e. whether this issue is included and how it is treated) Resource depletion surcharge and public subsidies (i.e. whether it is justified to include these as externalities)

— Use of the LCA based impact assessment approach [115, 116] for the parts of the energy system outside the country.

Recently, a framework has been developed that combines atmospheric dispersion and dose–response functions to establish generic relationships between pollution damage and geographical site [68, 69]. It has been demonstrated that this approach, which may guide the transferability/scaling of damage results, is correct to within one order of magnitude for a wide range of actual situations in Europe. Compared with the full scope, location specific application of the impact pathway approach, the resource savings of the new approach are substantial, though at the price of greater uncertainty.

5.3.3. Comparability

The problem of comparability was discussed in Section 4.9.2. Ideally, a comparison of impacts requires that they be expressed in the same units (implicitly, if not explicitly). The comparison should cover the same time, space and fuel cycle boundaries. However, inconsistencies cannot always be avoided. Some of the impacts cannot be quantified.

Currently, there is no agreed approach for comparing and weighting qualitative and quantitative indicators. Section 4 discussed an approach that is widely gaining acceptance. This task cannot be carried out by analysts alone. At some point in the decision process, the active participation of stakeholders and decision makers would be highly desirable. One reason for this necessity is that decision makers frequently disagree on objectives and social preferences, which need to be considered in a decision oriented valuation. A framework that allows one to address conflicting socio-economic and ecological criteria, and to accommodate trade-offs, is provided by MCA (e.g. Section 4 and Ref. [145]). There is a growing number of applications of this approach within the energy sector. One possibility, not yet fully explored, would be to combine monetary valuation with MCA as described in Section 4.

Appendix I

GLOBAL CLIMATE CHANGE[28]

The impacts of fossil fuel cycle emissions on global climate change are of great concern. Analysis of these effects needs to take into account many factors: population and economic growth; worldwide energy use; social factors and legislative action in the future; the uncertainty about the extent of the temperature increase; the effect of a temperature increase on regional climates; subsequent effects on ecosystems, human settlements and human health; the long time-scales involved; and the global nature of the impacts.

The basic approaches for estimating the impacts of global climate change are as follows:

(1) Estimate the CO_2 and other greenhouse gas emissions from each stage of the fuel chain.
(2) Use these estimates in a global climate model to estimate the global temperature rise.
(3) Use the temperature rise in an effects (impacts) model to estimate the possible impacts and damages.

Many scientific studies focus either on issues related to steps 1 and 2 or on those related to 2 and 3. More recently, attempts are being made at an ‘integrated assessment’ that also includes couplings between the different steps.

Global change models take into account, in various ways, key factors that affect the environmental impacts: accumulation of greenhouse gases in the atmosphere over time; CO_2 sinks, such as the oceans, that remove CO_2 from the atmosphere; radiative forcing (heat trapping capacity) associated with a marginal unit of emissions of a particular gas; the cooling effect of sulphate aerosols, which block sunlight; global temperature change as a function of radiative forcing; and environmental and economic consequences of global climate change. Further discussions are provided in Refs [79, 96, 146].

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[28] Material in this appendix is taken from Ref. [4], section 10.2, and Ref. [10], ch. 10.

I.1. POTENTIAL IMPACTS OF GLOBAL WARMING

I.1.1. Response of vegetation

The physiological processes in plants, including growth and reproduction, are strongly influenced by temperature. The effects depend on the mean temperature, the maximum and minimum temperatures, and the temperature pattern in the plant's environment [147]. Because these response characteristics vary greatly with species, and are largely unknown for many species of natural vegetation, quantitative response functions for temperatures that are appropriate for use in valuation are not well established. Potential CO_2–temperature interactions in plant response are even more poorly understood.

Moisture is the second important climatic variable likely to be part of global climate change. If a shortage of water available to a plant occurs, cell division and cell enlargement are adversely affected. In general, the more frequent and the longer the periods of water insufficiency during the growing season, the less the overall growth [147]. While elevated CO_2 can enhance water use efficiency in plants [148], the current state of science is inadequate to permit estimation of water–CO_2 interaction relationships.

I.1.2. Increases in crop and forest growth associated with enhanced atmospheric CO_2 concentrations

Vegetation is an important sink for atmospheric CO_2 through photosynthesis. Vegetation is also an important source of CO_2 through decomposition of dead organic matter. Forest ecosystems account for the dominant fraction (~67%) of global photosynthesis [148, 149]. It has been well documented that CO_2 enriched atmospheres, by stimulating photosynthesis, increase the growth of plants [148] and the accumulation of carbon in the biosphere [150]. As a result, increased plant growth must ultimately be considered in any economic analysis of the impacts of global change because there is potential economic benefit that offsets some of the various negative effects of climate change. Unfortunately, at the present time there are no quantitative response functions capable of adequately capturing not only long term tree growth responses to elevated CO_2 but also the interactions with fluctuating water and nutrient supplies, and competition between species [148].

Kimball [151] reviewed approximately seventy published reports on effects of CO_2 enrichment on the economic yield of 24 agricultural crop species. The responses across crop types (flower, fruit, grain, leaf, root and tuber, etc.) were expressed as mean relative yield increases, ranging from 12% (flower crops) to 52% (root and tuber crops). The average for all agricultural crops taken to a mature harvestable yield was 28%. These results are of little use, however, in the development of quantitative response functions since some of the studies involved only two CO_2 concentrations, all were either growth chamber or greenhouse studies with optimal nutrient and water regimes, and some studies potentially had suboptimal light quantities. Combining studies with widely varying environmental conditions may present an unrealistic interpretation of the true response. The studies reviewed by Kimball support the conclusion that, under controlled conditions, short term yield increases of approximately 30% might be expected from a range of agricultural crop species. Whether such increases would be of equal magnitude or would be sustained under field conditions is impossible to determine from the data that Kimball presents.

Scientists are concerned with the CO_2 fertilizer effect for two major reasons. Firstly, if the fertilizer effect is prominent, it can serve to explain a major portion of the carbon that is unexplained in many of the global carbon cycle models. The existence of a large fertilizer effect, and the increased forest growth that results, may serve to mitigate the climate change impact of CO_2 emissions. Therefore, understanding the fertilizer effect would allow the formulation of better predictions of climate change. Secondly, CO_2 fertilization may have a positive effect on agriculture through a variety of mechanisms. The increased growth may improve areal yields (of both agriculture and forestry), and the fertilizer effect is also hypothesized to increase the efficiency of water usage by plants, which would reduce the cost of production in areas that rely on irrigation or that become drier as climate changes.

Although it is scientifically feasible to test these effects, it is more difficult to test for the existence of indirect effects and constraints. For example, would increased CO_2 concentration also increase the presence and aggressiveness of weeds, which would have a negative effect on agricultural yields? Similarly, would higher temperatures increase pest populations? Insect populations are very likely to increase in a warmer global climate. Also, to what extent would the fertilizer effect be constrained by other factors which limit plant growth, such as the availability of nitrogen and other nutrients? Finally, is there a level of atmospheric CO_2 concentration above which further increases would not affect plant growth? Until these questions are satisfactorily answered there will be considerable controversy over the extent of the fertilizer effect.

Although there have been shown to be increases in nitrogen use efficiency with increased CO_2 that offset short term N shortages, as more and more N is sequestered in woody tissues there may be long term implications for ecosystem N cycling that would offset some of those benefits. Similarly, in forests where certain cation nutrients (e.g. Ca and K) are at or near levels limiting to growth, the benefits of enhanced CO_2 may be less than calculated. Bazzaz and Fajer [152] point out that interspecies competition, changing predator–prey interactions, changes in nutrient cycling and other factors can affect the growth response to enhanced CO_2. They postulate that it is not evident that increased CO_2 levels will lead to overall benefits to plants.

I.1.3. Response of agriculture

The impacts of climate change on total agricultural productivity can be mitigated to a degree by the ability of farmers to adapt. This is, of course, truer in large countries, such as the USA, that have a diversity of crops and climate zones [153] and good mechanisms for disseminating information on adaptive agricultural techniques to farmers [154]. However, even in the USA, agricultural communities and individual farmers have been hit hard throughout history by natural events (drought, flood, etc.) and economic events (high interest rates in the late 1970s, low prices, changing consumer preferences, etc.). The ability of these communities to adapt has been limited.

One study [155] addressed adaptation to climate change by considering the conditions in the 1930s. It found that in the absence of adaptation, output in 2030 as a result of climate change would be 20% lower than it would be without climate change, but that adaptation can virtually eliminate these losses. Cline [156] adjusted these results. He took into account the fact that the warming being considered is much larger (2.5° versus 1° in the 1930s), and found significant losses in agriculture (over 10% of output). Kane et al. [157] estimated that the losses to agriculture from climate change may be as much as $13 000 million per year ($1986), while Adams et al. [158] indicated that they could be as high as $34 000 million per year ($1982).

Smit et al. [159] reviewed literature suggesting potential shifts in cropping patterns under climate change. Under some scenarios, high yielding US corn varieties could replace Canadian varieties, and higher yielding winter wheats could replace northern spring wheat varieties. These changes could lead to alterations in the regional distribution and intensity of farming. Such shifts in crop patterns are expected worldwide.

I.1.4. Response of managed forest and grasslands

Since trees have relatively long lifetimes, the ability to adapt is less than that for agricultural crops [153]. Mature forests could be harvested and replanted with species that are appropriate for the new climatic conditions. Young forests could be replaced with appropriate species without too large a cost. According to the US National Academy of Sciences, the biggest impacts would be on ‘middle aged’ trees, which are too valuable to abandon, but which would be costly to maintain under less than favourable climatic conditions.

Musselman and Fox [160] concluded that temperate forests of the future would look different than they do now, or may exist in different geographical areas, necessitating that forest management decisions be made at the largest possible scale, while keeping local considerations in view.

I.1.5. Water resources

Since global change will include regional changes in precipitation, it will certainly have impacts on the regional distribution of surface water and groundwater resources. These impacts are difficult to quantify accurately with current information. However, they can be mitigated with adaptive projects such as the construction of dams and canals, although these take time, as do other sorts of adaptive responses [153]. Other adaptive responses would include genetically engineered improvements in the water efficiency of crops, technological innovation in water intensive industries (e.g. less wasteful irrigation methods) and the movement of activities to areas with sufficient water. However, certain regions would have less ability to react to specific regional changes (Gore [161] presents a popular summary of this topic).

I.1.6. Marine and coastal environments

The US National Academy of Sciences lists marine and coastal environment impacts as among the types of impact of global warming for which the least adaptive options exist. Nature is much slower in adapting than humans. Sea level rise may be sufficiently swift that existing wetlands are flooded more rapidly than new wetlands can form. In addition, one of the adaptive responses (building of dykes and sea walls) may have profound impacts on the coastal environment, as rising sea levels flood existing wetlands and sea walls prevent the creation of new wetlands. This could generate large ecological and economic impacts, as wetlands are critically important to marine and coastal ecosystems. However, the general view is that sea level rise will be rather slow.

I.1.7. Natural landscapes and ecosystems

For natural landscapes and ecosystems, successful adaptations are less likely. For a variety of reasons, the US National Academy of Sciences believes that the adaptability of natural ecosystems is more problematic than that of managed ecosystems. One reason for this assessment is that the time-scale of global climate change is rapid in comparison with the time-scale over which nature adapts. Another reason is the isolation of natural ecosystems by agricultural and urban land, which inhibits the migration of plant and animal species. The possibility of significant effects on forests and forest ecosystems cannot be precluded and should probably be expected.

I.1.8. Human health

Since human populations are found in the most extreme climates on the Earth, one can argue that the human species is remarkably adaptable to climatic differences. Changes in climate can change the distribution of vectors that carry human disease, and generate important health impacts in this indirect fashion. In developed countries, improvements in health technology take place at a sufficiently rapid pace to mitigate (but not eliminate) this concern. However, in poorer countries, this might not be the case [153].

I.1.9. Industry and energy

The chief concern for industry is the availability of sufficient water supplies [153]. Since the long term planning horizon for industry is short in relation to the period over which global change is likely to occur, industry should be able to adapt and relocate. As a result, some regions could gain and others lose in terms of economic activity and workers could experience significant dislocation costs.

I.1.10. Coastal settlements and structures

Global climate change could have a large impact on coastal structures as sea level rises. This is one of the few areas for which there is an existing body of research (e.g. Ref. [162]). Much opportunity for adaptation exists, however. Existing areas of high value can be protected by sea walls and other barriers. Existing areas of low value can be allowed to depreciate, and new structures constructed on higher ground. Such adaptations are of course dependent on the availability of higher ground. In general, for most places in the world, there are ways of adapting. However, in certain regions (regions with very low elevations near the sea), adaptation options are less likely to be successful in mitigating the effects of sea level rise. This lack of options is one reason why the Kyoto Protocol calls for limits on greenhouse gas emissions by the industrialized countries.

I.1.11. Importance of adaptation

The magnitude of the costs of potential global change is directly proportional to the number and size of opportunities to adapt. Although adaptation may mitigate some of the impacts of global warming, adaptation itself is costly. Table XXV [153] summarizes some of the major impact areas and the opportunities for adaptation. Regional impacts are likely to be much more severe than average national or global impacts. This concentration of impacts could make adaptation more difficult and will generate inequities between regions.

I.2. ECONOMIC VALUATION OF IMPACTS OF GLOBAL CLIMATE CHANGE

The marginal damage function is much more complex for CO_2 than for most other pollutants associated with the combustion of fossil fuels. There are several reasons

TABLE XXV. SENSITIVITY AND ADAPTABILITY OF HUMAN ACTIVITIES AND NATURAL SYSTEMS [153]

Activity or system	Low sensitivity	Sensitive but adaptation at some cost	Sensitive: adaptation problematic
Industry and energy	×		
Health	×		
Farming		×	
Managed forests and grasslands		×	
Water resources		×	
Tourism and recreation		×	
Settlements and coastal structures[a]		×	
Human migration[a]		×	
Political stability[a]		×	
Natural landscapes			×
Marine ecosystems			×

[a] Adaptation is much more problematic in those low income, less developed countries where a significant amount of densely inhabited land is subject to inundation.

for this, including the existence of major scientific uncertainties, non-linearities and time dependences. For these reasons, extreme caution must be taken in expressing estimates of the social costs of the global warming effect of fossil fuel chains.

I.2.1. Estimates of economic damages by Nordhaus and Cline

A study by Cline [156], in the form of a literature survey, focused on damages to the USA for an assumed doubling of CO_2 concentrations, and also for an extreme case in which CO_2 concentrations increased sufficiently to raise temperatures by 10°C on average. The study estimated damages associated with agriculture, sea level rise, heating and air-conditioning, water supply, human health, air pollution in general, ecological damage, and damage in several other minor categories. It was based on the assumption that a doubling of CO_2 concentrations over natural (pre-industrial) levels would lead to a warming of 2.5°C and concluded that this would produce annual damages about four times those estimated earlier by Nordhaus [163]. Nordhaus had omitted many damage categories (Ref. [156] presents more details on the limitations of the Nordhaus study and Nordhaus [79] discusses limitations of the Cline study [156]). Cline suggested that other developed countries in the temperate zone would have similar net losses, with losses in developing countries being higher as a percentage of GDP and losses in high latitude countries being less.

The work of Nordhaus is based on a dynamic economic growth model and does not incorporate non-market impacts. A summary of his results is presented in Table XXVI [163].

Cline [156] further considered that, without 'aggressive policy' action, temperatures would rise an additional 7.5° above the 2.5° rise associated with the CO_2 doubling benchmark in 300 years (an assumption based on extrapolating population, fuel use and income growth, following several analysts). Cline's scenario entails integrating under a non-linear damage function from 10° back to 2.5° warming. The benefits of avoiding this temperature increase are calculated to be several times larger than the benefits of avoiding the 2.5° warming.

Although the studies by Nordhaus and Cline have been widely discussed as pointing to drastically different levels of damage, their work is actually remarkably consistent. As Reilly and Richards [164] point out, if one looks at the GDP effects of an effective doubling of atmospheric CO_2 concentrations, both studies point to a loss of world GDP of approximately 1%. While Nordhaus only measures effects that actually influence GDP and produces estimates of approximately 0.25% of GDP, he

TABLE XXVI. IMPACT ESTIMATES FOR DIFFERENT SECTORS IN THE USA FOR DOUBLING OF CO_2 CONCENTRATIONS [163]

Sectors	Cost ($\$10^9$ (1981))
Severely affected sectors	
Farms	10.6 to –9.7
Forestry, fisheries, other	Small
Moderately affected sectors	
Construction	Negative
Water transportation	?
Energy and utilities:	
— Electricity demand	1.65
— Non-electrical space heating	–1.16
— Water and sanitation	Positive?
Real estate	
Damage from sea level rise:	
— Loss of land	1.5
— Protection of sheltered areas	0.9
— Protection of open coasts	2.8
Hotels, lodging, recreation	?
Total mean estimate	
National income	6.2
Percentage of national income	0.26

TABLE XXVII. ILLUSTRATION OF SENSITIVITY OF GLOBAL WARMING DAMAGES FROM COAL USE TO CHOICE OF FUNCTIONAL FORM AND DISCOUNT RATE [10]

Marginal value of CO_2 control (US \$/t)[a]	Damages for reference site (US \$/kW(e)·h)[b]
12.72[c,d]	0.014
10.9[d,e]	0.012
3.55[c,f]	0.004
5.27[d,f]	0.0059
2.0[c,g]	0.0029
3.45[e,g]	0.0038

[a] Taken from Reilly and Richards ([164], p. 55) and converted to 1989 dollars.
[b] Emissions from reference plant taken to be 1117 t CO_2/GW(e)·h.
[c] Quadratic formulation.
[d] Discount rate 2%.
[e] Linear formulation.
[f] Discount rate 5%.
[g] Discount rate 8%.

suggests that taking into account the effects that he did not measure would increase the measure to about 1–2% of GDP [156]. While Cline produces estimates for a more severe increase in CO_2 concentration (10° increase in mean global temperature over 300 years), when the doubling of atmospheric CO_2 is examined, and when non-market effects are added to the Nordhaus estimates, the two different reports are relatively consistent.

I.2.2. Illustrative estimates of damages

Reilly and Richards [164] developed estimates of the value of controlling CO_2 emissions in the context of developing a global warming potential index which is based on the relative values of controlling the various greenhouse gases. They based their damage estimates on the agricultural impacts of global warming, which were estimated by Kane et al. [157], and then extended these estimates to other economic sectors. They also deducted the fertilization benefits of increased CO_2 levels, which Reilly and Richards[29] report to equal \$1.33 per tonne of CO_2, when calculated with a 2% discount rate (\$0.65 at 5% and \$0.43 at 8%). Their results, which are calibrated to the emissions from a reference coal fired plant in the USA, are presented in Table XXVII [10].

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[29] Reilly and Richards [164] report this CO_2 fertilization effect, which is based on an assumed 20% increase in yield. This increase in yield then becomes an input to the agroeconomic model described by Kane et al. [157]. The \$1.33/ t estimate is an output of this model.

The method for extrapolating a damage estimate for a doubling of CO_2 levels in 100 years to a damage per tonne of CO_2 emissions is to assume that the total damages increase from zero to the estimated level according to some functional form, such as a linear, quadratic, logarithmic or exponential function. Then the damages at each point in time are estimated from this extrapolation function, converted to present value terms and summed. The damages are then divided by the total emissions to arrive at the estimate per tonne. Estimates are then converted to a per kilowatt-hour measure by multiplying by the tonnes of CO_2 per kilowatt-hour of generation for the power plant. Illustrative numerical results for a reference coal fired power plant are given in Table XXVIII [10].

Since all estimates are based on a particular time path of emissions, and because so few studies have taken place, it is difficult to make a quantitative assessment of the sensitivity of damages to the time path of emissions. This is critically important to policy for several reasons. Firstly, emissions might prove to be substantially different than the paths which are assumed in these economic studies. Secondly, policy makers must know how much more valuable it is to control emissions today than to wait to control them at some period in the future. Finally, the value of reducing CO_2 emissions will also depend on the time paths of reducing emissions of other greenhouse gases, as well as the time path of emissions of CO_2.

I.2.3. Summary of estimates from several studies

More recent studies (e.g. by Fankhauser [165]) consider each major region of the world separately. These studies acknowledge that this approach neglects interaction between impacts in different sectors and is not ideal, but is the best that can be achieved at present.

TABLE XXVIII. MARGINAL PRESENT VALUE OF CO_2 CONTROL FOR REFERENCE SITE[a]

Functional form	Marginal value (US \$/kW(e)·h)[b]
Quadratic	0.0057
Linear	0.0068

Source: Calculations in Ref. [10] based on Reilly and Richards' [164] use of damage estimates by Cline [156] and Nordhaus [163] of 1% of GDP from a doubling of CO_2 concentration in the atmosphere.

[a] Emissions from reference plant taken to be 1117 t CO_2/GW(e)·h.

[b] Discount rate 5%.

Impacts on the health and welfare of human populations are one of the most controversial areas. Some scenarios and analytical assumptions can give cost estimates for these impacts that are orders of magnitude larger than those summarized above. The key variable in this is the estimate of mortality due to natural disasters, including their effects on agricultural production. Impacts on agricultural production may be estimated on the basis of changes in supply and demand. However, in the case of disasters and their effects on food production in developing countries, such estimates significantly underestimate the full costs of these disasters. Drought and crop failure, or flooding and crop loss, may be exacerbated by global climate change and its effects on regional climatic systems. Increased mortality rates are therefore likely to be the dominant impact of global climate change, at least under many scenarios.

Studies that include these effects give cost estimates that are substantially higher than others. For example, Hohmeyer and Gartner [166] assumed that reduced soil moisture would lower agricultural yields in many regions and that subsequent losses in production would fall mainly on the poorest people in the poorest countries. They postulated an additional 45 million deaths per year from starvation alone. This estimate is in contrast to Fankhauser's estimate of 240 000 deaths annually from all global warming related impacts.

The valuation of mortality poses additional questions. Hohmeyer and Gartner [166] valued each life lost using a value of a statistical life of \$1 million, somewhat less than but of the same order of magnitude as the 2.6 million ECU used in the ExternE study and the \$3.5 million used in the US part of the US–EC Fuel Cycle Study. An alternative, proposed by Fankhauser, is to use a lower value of a statistical life for developing countries — \$0.1 million has been suggested, compared with \$1.5 million for countries within the Organisation for Economic Co-operation and Development (OECD). This difference should be interpreted only as a WTP (which is income dependent) rather than as any assessment of the relative worth of

TABLE XXIX. ESTIMATES OF DAMAGES FROM GLOBAL CLIMATE CHANGE DUE TO CO_2 EMISSIONS OF COAL FUEL CHAIN [4]

Source of estimate	Damages (mECU/kW(e)·h) for discount rate of:			
	0%	1%	3%	10%
Cline [156]	14.9		2.2	0.6
Fankhauser [165]	10.4		1.5	0.4
Hohmeyer and Gartner [166]	5030		770	190
Tol [167]		18.3	11.7	2.6

individuals in different countries. The issues of valuing the costs of global warming are inseparable from broader questions of development and world economic order.

Table XXIX, from the ExternE study [4], summarizes estimates of damages from global warming due to CO_2 emissions from the coal fuel chain. The estimates by Cline [156] and Fankhauser [165] for a 3–10% discount rate are consistent with those in Table XXVIII from the US part of the US–EC Fuel Cycle Study [10]. The estimates by Tol [167] and especially by Hohmeyer and Gartner [166] are much higher. As previously discussed, these estimates reflect a higher value of a statistical life, as well as the assessment that the number of deaths per year is two orders of magnitude greater than Fankhauser's estimate.

I.2.4. Uncertainty in estimates

Estimates of economic damages due to CO_2 emissions have been included in this report for illustrative purposes and to summarize published estimates. While there is considerable uncertainty surrounding these estimates, they have been reported to reflect the work that has been published to date. A better understanding of the benefits and damages associated with global warming awaits the measurement of non-market impacts and the implementation of studies which show the sensitivity of damage estimates to different assumptions about the time paths of emissions. In addition, better knowledge of scientific relationships is required to improve understanding of economic damages.

Appendix II

ENERGY SECURITY

Analysts who need to estimate the health and environmental impacts of electricity options will probably not be required to do original research on energy security, in part because its impacts do not depend on the specific locations of power plants within a country. Therefore, this appendix is intended to provide analysts with basic information on the key concepts, estimates of the range of possible energy security costs associated with the use of oil, and the major points of contention about these costs.

The term energy security refers to the economic security of a country that is relatively dependent on oil imports from one or more suppliers with considerable market power (i.e. OPEC) and/or that is vulnerable to oil price shocks. Energy security costs may exist for an oil importing country when its economic welfare is not as great as it could be if the oil market were efficient. The magnitude of these costs depends on the degree of market power that OPEC possesses, on the concentration of supply within OPEC and on the ability of the oil importing country to respond to oil price shocks. The extent to which these factors exist is contentious.

Energy security costs, to the extent that they exist, have two major components.[30] One component is the economic rent that OPEC extracts from the market through its power as a cartel. Theoretically, an oil importer with considerable market power, such as the USA, could recover this rent owing to its monopsony power as a major consumer of oil. If the oil importer does not exercise its monopsony power, then the price of oil is ‘unnecessarily’ high. Oil importing countries with limited economic, political or military power generally cannot recover any economic rent. Thus, in theory, this rent is not an energy security cost. However, such countries may be extremely vulnerable to the second energy security cost component, which occurs when there are sudden changes in the price or availability of imported oil. Such a price shock results in spillover effects on the total performance of the economy, which are not reflected in market prices, as the economy adjusts to the shock.

Analysts differ greatly in their assessments of the magnitude of these costs. There are basically two positions. The first is that these costs are unlikely to be very large, or that they are not relevant to policy because there are no practical options available to ameliorate these costs. Bohi and Toman are the major proponents of this position [168–170]. The second position is that they are likely to be sizeable and policy relevant. A number of analysts take the latter position [171–173]. Each

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[30] This appendix focuses on economic considerations and does not consider military and other related costs associated with the defence of oil supplies.

position is supported by a number of careful studies. However, the studies differ in their assumptions, data and statistical methods. Each side in the debate is critical of data, methods and analyses used in the studies that the other side uses to buttress its arguments.

This report does not attempt to resolve the issue, but rather to summarize the positions, and thus the state of the literature on energy security costs. Proponents of each position agree on the need for more detailed analysis of key points of contention.

Thus, there is no recommended estimate of the energy security costs of oil fuel cycles. Instead, the major arguments of both sides in this debate are summarized here. The summary is organized so that the two energy security components are discussed separately, and the key arguments of each side of the debate are presented.

II.1. CARTEL RENTS AND LONG TERM COST OF OIL IMPORTS

In a perfectly competitive market, the price of oil completely reflects its cost (at the margin). However, when sellers such as OPEC exercise some market power, the price may lie above the perfectly competitive level. If an oil importer such as the USA can take advantage of its position as a major consumer of oil to offset this price premium, then the importer has some monopsony power where, because it is such a large consumer, it can affect market conditions, such as prices, on its own. If a country can successfully use its monopsony power to reduce the price of oil, but does not do so, then this inaction is an opportunity cost. These costs, to the extent that they exist, occur over long periods, in contrast to the short term effects related to oil price volatility, which are discussed later.

II.1.1. The view that cartel rents are likely to be significant[31]

The viewpoint that there are significant and policy relevant cartel rents is based on the argument that oil supply is not provided in a competitive market, and that the importer's policies can countervail the exporters' market power. Analysts justify these claims with three reasons:

(a) Empirical evidence that suggests that OPEC behaviour conforms more closely to an (imperfect) output sharing cartel than to a confederation of competitive suppliers [175–177];

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[31] Based largely on Ref. [174].

(b) The fact that most estimates of the marginal cost of production are well below the prevailing price;

(c) The contention that any price premium associated with the depletability of oil is likely to be small, given the large resource base and the ability to replenish reserves with improved technology and greater effort.

Although oil prices have been stable and the influence of OPEC has been seemingly diminished in the past several years, many analysts argue that OPEC still functions as a cartel, even if not a completely effective one. For example, although Adelman sees increasing pressure on OPEC, he warns that it would be imprudent to expect the cartel to disappear any time soon ([171], p. 11). In fact, according to Greene et al. [173], OPEC's increasing market share will probably increase its monopoly market power in the future, as well as the risk of oil market disruptions.

Leiby et al. [174] used the 1994 version of the US Department of Energy's Oil Market Simulation Model (OMS94) to estimate the marginal benefit of a reduction in oil imports. They considered different assumptions about the response of OPEC supply to changes in US import demand.[32] With an OPEC supply elasticity of 5, the marginal cartel rent is \$0.90/barrel (\$1993). With an elasticity of 1, it is \$2.86/barrel. These rents, to the extent that they exist, are part of the energy security cost of the oil fuel cycle.

II.1.2. The view that cartel rents are unlikely to be large or policy relevant

Other analysts have a viewpoint opposite to the one mentioned above. They argue that recoverable cartel rents are unlikely to be large. These analysts are skeptical of OPEC's effectiveness as a cartel. For example, Bohi and Toman inspected petroleum production data and questioned whether OPEC supply behaviour has been consistent with that of a cartel. They suggest that Dahl and Yucel's [177] analysis has problems with the specification of the econometric framework ([178], p. 38). They further note the increasing rivalries among the countries within OPEC. Stagliano [170] argues that the power of OPEC is more a 'ghost' than a reality. His assessment is that the fears of OPEC's potential ability to curb oil supplies to the USA, or unexpectedly to raise prices to economy damaging levels, are unfounded. He regards

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[32] The model summarizes OPEC price response to reductions in demand with an elasticity, although, strictly speaking, the response function of a cartel does not correspond to a well defined supply curve.

OPEC to be ineffective as a cartel operating in a global, generally free, oil trading system ([170] p. 8).

These analysts also question whether it would be wise for the USA to use its monopsony power to recover cartel rents, even if they exist. They contend that monopsony effects are usually thought to be only 'pecuniary' externalities that redistribute rents but do not bear on market efficiency. When the rent redistribution involves rent transfers out of the purchasing country, the size of these wealth transfers may be a concern for policy makers even if the market is efficient from a global perspective. However, these analysts say that it is not necessarily advantageous to exploit a potential monopsony position. In fact, the USA, for example, eschews the exercise of monopsony power in a number of international markets. To argue for the exploitation of monopsony in the world oil market, it is necessary to conclude that the policy decision can affect world prices and that it will not provoke a retaliation by exporters which would leave the country in a worse condition.

Should monopsony effects be included in fuel cycle evaluations? The view of Bohi and Toman is that they are not relevant to individual local fuel chain decisions because monopsony effects operate only at a national scale. They contend that these effects cannot be addressed directly in the absence of some means for co-ordinating oil demands at a national level. They state that even at a national level, the capacity of a country to influence world oil prices by curbing demand or imports is likely to be limited. They suggest that the national government can take concerns over oil import costs into account by promoting domestic sources of oil or by the design of R&D policies that favour research on energy technologies that use energy sources other than oil.

II.2. COSTS OF OIL MARKET DISRUPTIONS

Like any other commodity, oil fluctuates in price. More importantly, its supply is geographically concentrated. Some analysts contend that this supply region is politically unstable, making it subject to disruptions that cause oil price shocks. When these shocks occur, payments for oil imports increase greatly. Demand for oil is relatively inelastic in the short run. Thus, oil price shocks may also have a ripple effect throughout the economy.

As in the case of the debate about cartel rents during normal (i.e. stable) markets, there are two divergent views about the costs of oil market disruptions. One view is that the increase in payments for imports is an external cost and that the macroeconomic adjustments during oil price shocks are large and attributable to the shocks themselves. The other view is that increased payments for oil imports are part of a competitive market and that there is little evidence to support the claim that the macroeconomic adjustment costs are large.

II.2.1. The view that disruptions are likely to lead to significant externalities[33]

According to this view, oil market disruptions lead directly, or indirectly, to price shocks. When prices increase, the principal losses are increased payments for imports and macroeconomic adjustment losses. Estimates of these losses depend, of course, on the probabilities of disruptions of different sizes. The following estimates take these probabilities into account.

II.2.1.1. Increased payment for imports

The price of oil, according to this view, increases greatly during disruptions, even though demand decreases. The net effect is that more is paid for imported oil. This increase in cost may not have been taken into account by producers and consumers in any fuel related investments that they made previously. According to this line of reasoning, to the extent that oil consumers and producers do not fully anticipate and insure against either the microeconomic or macroeconomic effects of oil price shocks, the increase in the oil import bill will not reflect a cost fully captured in the current price of oil.

Leiby et al. [174] used the DOE's OMS94 model to estimate a range of values for the marginal external costs of the increase in import costs during disruptions. Their analysis took into account a range of possible disruption probabilities, the existence of cartel rents, effects of imports on disruption probabilities, and the degree of anticipation and hedging. Their results generally range from zero (if there is complete anticipation and hedging) to \$2.11/barrel (\$1993).

II.2.1.2. Macroeconomic adjustment costs

Analysts who suggest that energy security costs are significant contend that oil disruptions lead to large costs to the macroeconomy. Whereas wealth transfers to pay for imports depend on the level of energy prices and the volume of the energy imports, macroeconomic adjustment losses depend on the change in energy prices and the volume of the total (not just imported) energy consumption.

The reasoning of these analysts is that when the oil price suddenly increases, real wages will not adjust to maintain employment, leading to unemployment. The use of energy consuming capital equipment will also decline, reducing productivity throughout the economy. The losses are compounded by difficulties in reallocating factors of production in response to changes in the mix of final demand brought about by changes in product prices.

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[33] Taken from Ref. [174].

Over a dozen empirical studies have linked GNP losses to oil price increases. Among the more recent studies are Refs [172, 179]. The GNP adjustment losses estimated in these studies depend on the size of the proportional price increase as well as on the vulnerability of the macroeconomy to adjustment losses for a price shock of a given size. Leiby et al. [174] calculated a range of macroeconomic adjustment cost estimates. The range reflects different assumptions about disruption probabilities, effects of imports on disruption risk, and GNP elasticity. The range is from zero to \$6.48/barrel (\$1993), with a 'narrowed range' of \$0.44/barrel to \$1.60/barrel, reflecting a narrower range of values for these assumptions.

II.2.2. The view that disruptions are unlikely to lead to significant externalities

An alternative viewpoint is that there may not be large spillover costs caused by oil price volatility. These doubts are based on the causes of rigid adjustment in the economy and the degree to which volatility of energy prices is accommodated ex ante.[34]

Empirical studies of the macroeconomic effects of energy price shocks do not try to distinguish between internalized and externalized costs. Therefore, the best that can be accomplished is to try to assess the importance of the gross macroeconomic costs of energy price shocks and to draw inferences about the empirical significance of the externality component.

The evidence about the gross costs at the national level is mixed. The coincidence in the timing of the two oil price increases and two recessions during the 1970s has led many observers to believe that the effects of energy price shocks on the economy are large. However, some analysts contend that equations of models used to reach these conclusions employ parameters estimated from limited experience with price shocks over the period 1950–1980. During this period, real oil prices were stable or falling except for the two brief increases during the 1970s. Thus, the conclusions of the models regarding the relationship between oil price increases and GNP will be determined by the experience with the two recessions that followed the 1970s price shocks (even though this experience may not be representative of the true energy–economy relationship). These analysts explain the recessions experienced in some countries by factors other than energy prices, such as differences in macroeconomic stabilization policies. In other words, according to this viewpoint, it

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[34] Although the timing of oil price shocks is unknown, producers and consumers account for the possibility when they make decisions. One way of hedging against price shocks is through the oil futures market (some analysts state that the effectiveness of this hedging has not been empirically measured).

is possible that the econometric models are confusing the effects of the deflationary macroeconomic policies with those of changes in oil prices.

The doubts of these analysts are based on their examination of disaggregated industry data for Germany, Japan, the United Kingdom and the USA for explanations of the experiences of these countries during the 1973–1974 and 1979–1980 shocks. These analysts explain that energy prices may have had little to do with the macroeconomic problems of the 1970s. They find that, within each country, the industries hit hardest are quite dissimilar from one recession to the next and, for each recession, the industries hit hardest are dissimilar in the four countries. There are no significant negative correlations between energy intensity and changes in output, employment or capital formation for any of the four countries. Nor does the evidence suggest that adjustment costs caused by changes in the composition of final demand are more severe in energy intensive sectors. Finally, these analysts suggest that, in contrast with the rigid-wages argument, changes in real wages appeared to vary negatively with energy intensity in the two shock periods. This relation would suggest that wages were more responsive in labour markets where unemployment was more serious.

An alternative hypothesis suggested by these analysts is that the industrialized countries were already combating inflation when the oil price shocks occurred[35], and that these price shocks further reduced the ability of the countries' economies to mitigate inflation. Given that Japan was the only industrial country to avoid a recession after the 1979 oil shock, it is plausible that the monetary authorities rather than energy prices were to blame for the recessions in other countries.

More study is required to understand better the nature of energy–economy interactions at the national and regional levels. If nothing definitive can be said about the gross economic costs of energy price shocks, it follows that even less can be said about the magnitude of any embedded externalities that are relevant for comparing fuel chains at a local or national level.

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[35] Except for Japan in 1979.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Ball, D.J.	University of East Anglia, United Kingdom
Beutier, D.	NUSYS, France
Boone, C.	Ontario Hydro, Canada
Borysiewicz, M.	Institute of Environmental Protection, Poland
Demin, V.	Russian Research Center, Kurchatov Institute, Russian Federation
Dinnie, K.S.	Ontario Hydro, Canada
Dreicer, M.	Environmental Assessments, United States of America
Dutkiewicz, R.	University of Cape Town, South Africa
Eyre, N.	Eyre Energy Environment, United Kingdom
Frei, C.W.	Ecole polytechnique fédérale de Lausanne, Switzerland
Gómez, D.R.	Comisión Nacional de Energía Atómica, Argentina
Gröndalen, O.	Sydkraft Konsult AB, Sweden
Hirschberg, S.	Paul Scherrer Institute, Switzerland
Hlavatá, A.H.	Ministry of the Environment, Slovakia
Hobbs, B.	Johns Hopkins University, United States of America
King, F.	International Atomic Energy Agency
Kolev, I.	Bulgarian Academy of Sciences, Bulgaria

Kollas, J.G.	Democritos National Research Centre for the Physical Sciences, Greece
Kiločány, F.	Ministry of the Environment, Slovakia
Kontić, B.	Jožef Stefan Institute, Slovenia
Krewitt, W.	University of Stuttgart, Germany
Lee, R.	Oak Ridge National Laboratory, United States of America
Linares, P.	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain
Linnerooth-Bayer, J.	International Institute for Applied Systems Analysis
Matsuki, Y.	International Atomic Energy Agency
Mirasgentis, S.	National Technical University of Athens, Greece
Morici, A.	National Agency for Environmental Protection, Italy
Nagano, K.	Central Research Institute of Electric Power Industry, Japan
Novak, I.	Ministry of Economic Affairs, Slovenia
Pan, Z.	Commission of Science and Technology, China
Rábago, I.	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain
Rabl, A.	Ecole des mines, France
Różycki, S.J.	Ministry of Environmental Protection, Poland
Russ, P.	Institute for Prospective Technological Studies, Spain
Škerbinek, G.	Electric Utility of Slovenia, Slovenia

Strupczewski, A.	International Atomic Energy Agency
Sugiyama, T.	Central Research Institute of Electric Power Industry, Japan
Sundell-Bergman, S.	Vattenfall Energisystem AB, Sweden
Swaton, E.	International Atomic Energy Agency
Tamari, A.	Ministry of Energy, Israel
Taniguchi, T.	Central Research Institute of Electric Power Industry, Japan
Török, S.J.	United Nations Economic and Social Commission for Asia and the Pacific
Triputti, I.	Ente Nazionale per l'Energia Elettrica spa, Italy
Wilson, R.	Harvard University, United States of America
Zanardi, V.	University of East Anglia, United Kingdom
Zarkasi, A.S.	National Atomic Energy Agency, Indonesia

Research Co-ordination Meetings

Vienna, Austria: 26–30 September 1994
Athens, Greece: 13–17 November 1995
Vienna, Austria: 7–11 April 1997

Consultants Meetings

Vienna, Austria: 13–17 March 1995, 30 October–3 November 1995, 13–24 May 1996

Technical Committee Meeting

Vienna, Austria: 13–17 May 1996