SESE-I

Physics, Systems Analysis and Economics of Fusion Power Plants

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ABSTRACT. Fusion power is being developed because of its large resource base, low environmental impact and high levels of intrinsic safety. It is important, however, to investigate the economics of a future fusion power plant to check that the electricity produced can, in fact, have a market. Using systems code analysis, including costing algorithms, this paper gives the cost of electricity expected from a range of fusion power plants, assuming that they are brought into successful operation. Although this paper does not purport to show that a first generation of fusion plants is likely to be the cheapest option for a future energy source, such plants look likely to have a market in some countries even without taking account of fusion's environmental advantages. With improved technological maturity fusion looks likely to have a widespread potential market particularly if the value of its environmental advantages are captured, for instance through avoiding a carbon tax.

1. Introduction

As an introduction to the background world energy markets in which fusion will have to compete, Figure 1 illustrates the variation in world industrial electricity prices over time and between countries. Different countries use a different selection of technologies and fuels for their electricity generation, and the costs of these technologies and fuels vary both geographically and with time which, along with different market conditions, lead to the large variation in prices worldwide.

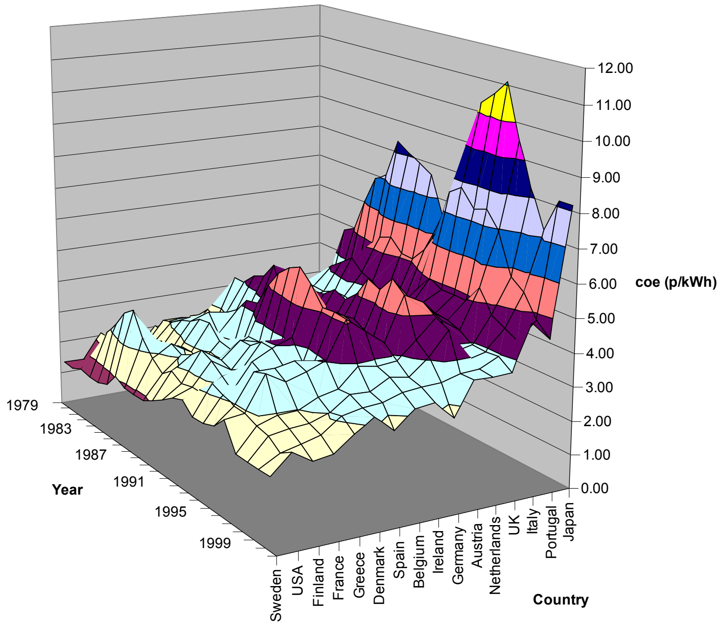

Figure 1: The industrial price of electricity varies around the world and over time depending both on the choice of technologies and fuels and their prices in the local markets. [1]. Prices are industrial prices without taxation given in money of the year.

The data in Figure 1 illustrates the difficulty in giving precise targets that a fusion power plant must achieve in order to be economically viable, particularly in a future market whose properties are not known. For example the UK wholesale electricity spot price in the first quarter of 2005 was 80% higher than in the first quarter of 2004 [2].

In order to study the cost of electricity expected from a fusion power plant, we need a tool to study what a power plant might look like and how much it would be expected to cost. Although we don't have a full engineering design of a fusion power plant, all of the key components are identified and costing algorithms, validated by comparison with existing machines and with designs of new machines as well as similar technologies used elsewhere, allows a reasonable estimate of the costs expected of a fusion power plant. This is more reliable than might be expected because around half the costs are expected to lie in conventional items such as turbines and buildings, whose costs are already well established.

The tool used in the studies reported here is a systems code called PROCESS [3], which couples the physics equations set up during the conceptual designs phase of ITER [4] with models of key technology components, particularly superconducting coils and stresses, and satisfies power balance requirements and radial build consistency to give a self-consistent model of a power plant. This code has been benchmarked against independent studies, including design work for ITER as well as US power plant studies. An example of this benchmarking is given in Figure 2 which shows a comparison between the ITER costs given in ITER documentation [5], with those from PROCESS. Comparison with US studies can be found in [6].

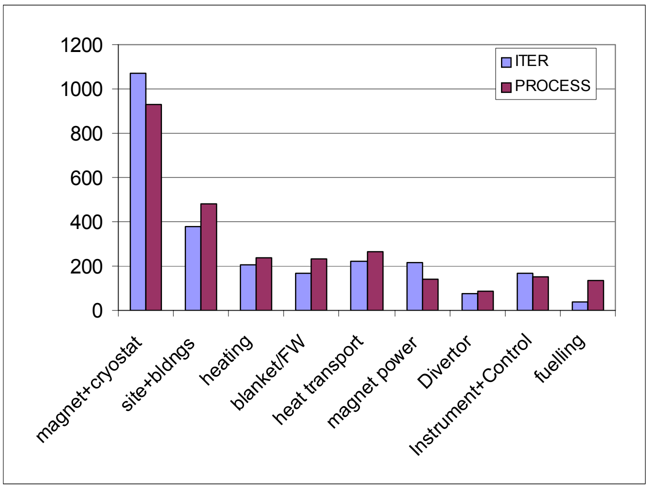

Figure 2: Benchmarking studies of design costs for ITER from ITER studies and from PROCESS.

The link between power plant costs and cost of electricity is through the levelised cost methodology

$$\text{coe} = \frac{\text{fcr} \times \text{CAP} + \text{OM} + \text{REP} + \text{FUEL} + \text{DECOM}}{8760 \times \text{A} \times \text{P}_\text{e}}$$

where fcr is the levelised annual charge on capital, CAP is the total capital cost, OM the annual operation and maintenance cost, REP the annual cost of replacement items, FUEL the deuterium and tritium costs, DECOM the cost of an accumulating decommissioning fund, A is the availability and P_e the net electrical output in kW. 8760 is the number of hours in one year.

2. First Generation Fusion Power Plants

The likely design of a first generation fusion power plant is still a matter of debate and the outcome will depend in part on the rate at which the development is pursued. On a fast track route to fusion, the strategy would be to find physics and technology solutions, including materials, that are good enough to proceed, even though further work might lead to beneficial advances. To try to cover the range of possibilities, the Power Plant Conceptual Study (PPCS) [7], carried out by the EU, explored a range of possible plants (A to D), with different levels of improvement in physics and technology. This range included a steel based, water cooled plant (Model A), through to a silicon carbide composite plant with high temperature coolant and high efficiency (Model D). The latter could not be considered to be a first generation plant, but the other plant models investigated could.

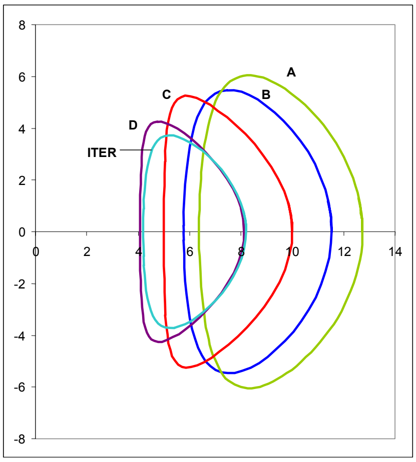

Figure 3: Illustration of the plasma size and shape for the four PPCS models, compared to ITER.

Before looking at the PPCS plant models, it is interesting to consider as a reference a power plant based around ITER assumptions. This is expected to be very pessimistic because ITER, as the first machine to produce very high levels of fusion power (designed for 500 MW), is designed for relatively low values of β_N and low power density, partly in order to limit the step-up in required power handling. It is assumed that ITER will develop beyond its design point as experience in operating at high levels of fusion power is obtained. If the β_N value ranges from 1.7 to 3.4, with corresponding levels of other key parameters, the cost of electricity from a tenth-of a-kind plant of such a design would be in the range 8 to 15c/kWh [8]. At the lower end of this range, a system could be introduced into a future (coal fired) electricity market with an equivalent carbon tax of 40 €/tonne CO_2 compared to a present price of around 23€/tonne in the EU emissions trading scheme (on 27/6/05). To compete with gas, the gas price would need to be above 6€/GJ, which is in fact presently the case in some markets. The higher end of the range does not look as though it would be economically competitive with coal unless a carbon tax equivalent to 100 €/tonne were in force.

Having seen where an ITER-based plant might lie terms of economics, poor but a possible option in some markets, we move on to the EU power plant studies (PPCS). In these studies it is assumed that ITER will continue the progress that has been made in the fusion programme over the last decades and lead to more efficient power plants: the difficulty is to predict how much progress may be made. This led to the study of a range of options, from the lowest level of scientific and technological development in Model A through to more sophisticated plants, culminating in Model D. Models A and B are relatively unambitious in physics performance, with the need for high plasma current and substantial current drive power, with high radiated power to protect the divertor. These issues and their impact are discussed below.

In the systems studies carried out for the PPCS, one area that was particularly important was the interaction between divertor heat load, current drive power and confinement. The interaction is through the need to radiate power rather than conduct it to the divertor, effectively reducing the plasma heating power. This drives the design to larger size, higher plasma current, to increase the energy confinement, and consequently to higher current drive power.

Figure 4 shows an illustration of the divertor/current drive interaction by allowing the confinement multiplier, H, to vary in a generic power plant design in which the divertor heat load is held fixed. As the H-factor is increased, the current needed to achieve the required confinement reduces and the current drive power reduces. The reduction in current is doubly beneficial for current drive as the fraction of bootstrap current also increases reducing the fraction of current which must be maintained by current drive.

It is in the area of divertor protection and current drive that there is the biggest difference between PPCS Models A and B on the one hand, and Models C and D on the other. In Models A and B the full penalty of protecting the divertor, implied by the relations given in [4], is applied, leading to power plants with high radiation, high current drive power. The more advanced assumptions in Models C and D relax this assumption (fully for Model D and partially for Model C) and further reduce the current drive power by operating at higher safety factor. The fusion power density is maintained in Models C and D by allowing higher shaping and higher β_N. The PPCS plant parameters are summarised in Table I, whilst Figure 5 shows the radiated power fraction for the plant models and Figure 6 the current drive power.

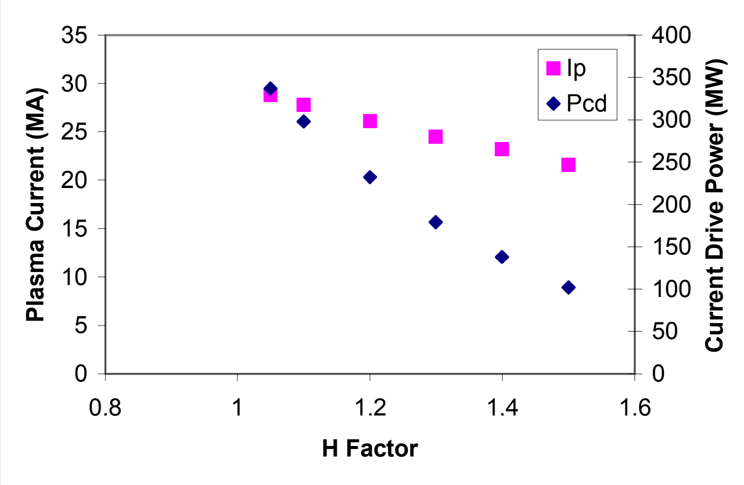

Figure 4: As the H-factor increases, the plasma current needed to maintain sufficient confinement reduces, reducing the current drive power.

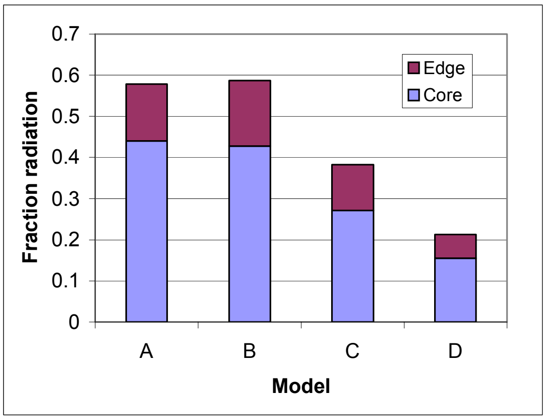

Figure 5: The radiated power fraction distinguishes between plant models with A and B requiring high radiation to protect the divertor.

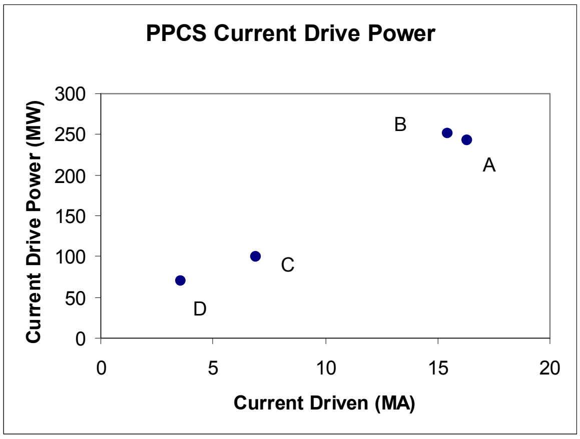

Figure 6: The total current drive power in the PPCS plant models falls from high values in Models A and B to modest values for Models C and D.

TABLE I: KEY PARAMETERS OF THE PPCS PLANT MODELS

	Model A	**Model B**	**Model C**
Major radius (m)	9.55	8.6	7.5
Toroidal field on axis (T)	7.0	6.9	6.0
Plasma Current (MA)	30.5	28.0	20.1
n/n_G	1.2	1.2	1.5
β_N (thermal,total)	2.8, 3.5	2.7, 3.4	3.1, 4.0
Divertor Peak Load (MW/m^2)	15	10	10
Net electric power (GW)	1.55	1.33	1.45
Fusion Power (GW)	5.00	3.6	3.4
Current drive power (GW)	0.246	0.270	0.112

3. Economics of First Generation Power Plants

Having established a range of power plant concepts, three of which are considered candidate options for a first generation of power plants, we can consider their likely economic performance. In addition to the technical aspects of the plant and the associated costs, we need to make assumptions about the availability of the plants, the amount of technological learning involved in producing multiple plants, and the discount rate to be used in determining the cost of capital.

The availability of the plants is assumed to be 75% based on analysis of maintenance schemes made as part of the PPCS, although this will set a challenging target for materials lifetimes. Only a materials test facility such as IFMIF can show whether sufficient material lifetimes can be achieved.

Technological learning, the reduction in costs as experience of building plants grows, is assumed to vary with a progress ratio (the reduction in cost with each doubling of production) of 0.82. This is consistent both with the learning found in related systems, such as the superconducting magnets in MRI scanners, and with other energy systems. The learning is only applied here to the fusion specific items, not the conventional cost items for which no learning is assumed as these technologies are taken to be mature.

The choice of discount rate is very important because around two thirds of the cost of electricity comes from the capital. The choice depends on whether to consider public sector or private sector investment, but here we consider an intermediate case with a real discount rate of 6%.

Figure 7 illustrates the importance of capital in determining fusion costs, showing the breakdown of the cost of electricity from the PPCS plant models into the main components; capital, operation and maintenance, replacement of divertor and blanket, fuel and decommissioning. Figure 8 gives a breakdown of the capital costs into the main components, showing the importance of the cost of magnets and cryostat and highlighting the different contribution the divertor makes to capital, where it is relatively low, compared to cost of electricity, where it is relatively high because of the frequent replacement.

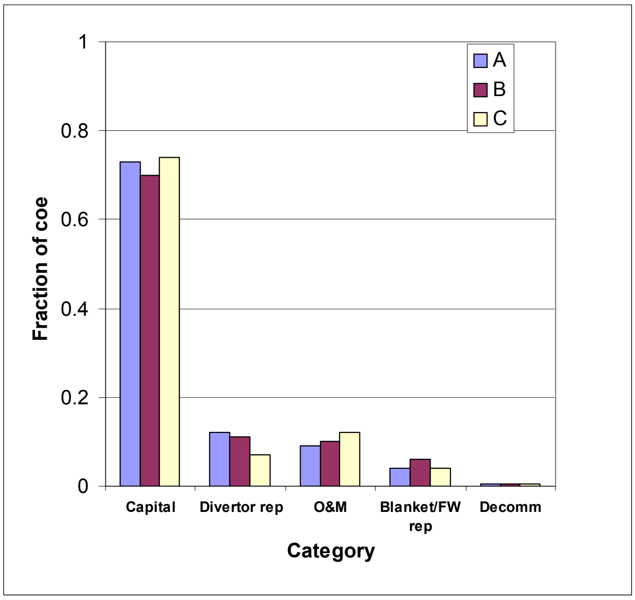

Figure 7: Breakdown of the cost of electricity of the PPCS models into their main components.

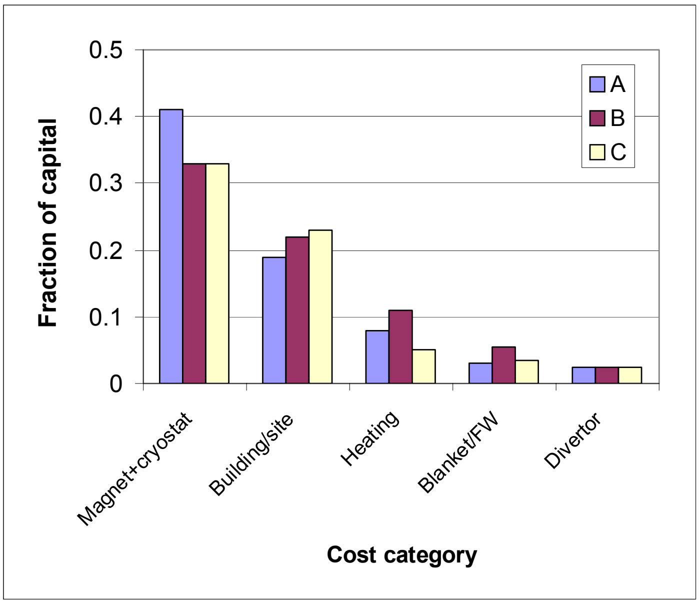

Figure 8: Breakdown of the capital costs into main categories for the PPCS plant models.

A valuable way of looking at the costs of the different PPCS plant models is to look at the specific costs, that is the cost per Watt of fusion power and per Watt of electrical power. Figure 9 illustrates this and reveals an interesting feature that the specific cost per Watt of fusion power is similar across the PPCS plant models but, because of the varying efficiency of the plant models, the cost per Watt of electricity reduces in moving from Model A to C. This result is somewhat surprising in the light of the advances assumed in the physics in Model C but is due to the fact that although operating at higher β_N, Model C also operates at reduced plasma current so the value of power density is not much higher. The main effect of the changes is to allow operation at lower current and dramatically lower current drive power which, coupled with increasing thermodynamic efficiency, leads to a cost of electricity which reduces from Model A to Model C.

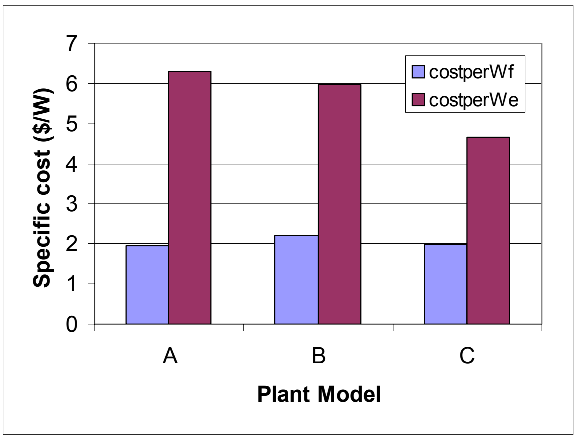

Figure 9: The specific costs of the PPCS plant models show that in terms of cost per Watt of fusion power, the plants are surprisingly similar, however the increasing efficiency of the plants leads to a reducing cost per Watt of electrical power. These costs assume a tenth of a kind plant.

Putting together all these aspects of the costs we can look at the cost of electricity of first-generation fusion power plants. Here we will have to make a judgement of how many plants are involved, in order to introduce the technological learning appropriately. We would usually consider the tenth of a kind plant however 10 plants of this sort would only be expected to make 0.3% contribution to the future electricity market, which seems too small even for a first generation. We will therefore also look at the possibility of 100 plants worldwide.

Figure 10 shows the cost of electricity for the PPCS plants plotted against the learning factor, which represents the cost of the fusion specific items compared to the first of a kind. For a tenth of a kind with a progress ratio of 0.82, this factor will be 0.52, whilst for a 100th of a kind plant this will be 0.27. Taking this as the range for the technological learning gives a range for the cost of electricity for plant Models A to C of 4.5c/kWh to 8c/kWh.

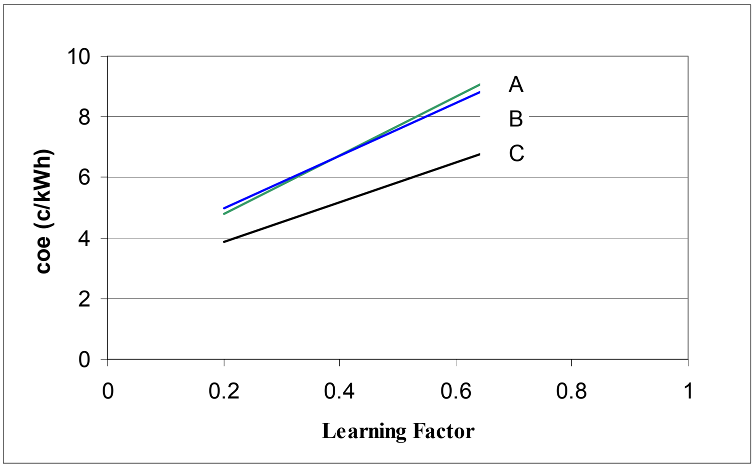

Figure 10: The cost of electricity reduces as technological learning reduces the learning factor. A tenth of a kind plant would be expected to lie around a learning factor of 0.5, whilst a 100th of a kind plant would be around 0.3. The learning factor is only applied to the fusion specific cost items.

4. Further Developments

Although not considered here as an option for a first generation fusion power plant, there was also a very advanced PPCS plant model, Model D, which used silicon carbide composite materials and high temperature coolant to achieve very high thermodynamic efficiency, reducing the cost of electricity. This would allow the possibility of lower generation costs, as would the widespread adoption of fusion to become a mature technology through achieving 30% of the future electricity market. Both of these cases, a very advanced plant model or a high degree of technological learning involve a greater degree of extrapolation than the earlier estimates so should be considered to be less reliable. The costs in these cases would lie in the 3-5c/kWh range. This is a very ambitious target, not considered realistic for early generation fusion power.

5. Comparisons

An important part of an analysis such as this is to consider how fusion might compare with other energy sources. Of course the future market for electricity is very uncertain, particularly in the light of the enormous variation in the present market which was illustrated in Figure 1. To allow a comparison, data have been taken from a recent publication [9] which gives estimates from a range of countries of the projected cost of electricity from near term plants.

Such a comparison should contain enormous numbers of caveats and the data used are already out of date because the price of gas assumed in the publication are substantially below the present market price of gas. This has been allowed for by using the present UK market price of gas in the upper gas estimate. Both coal and gas include the cost of CO_2 emissions as presently given by the cost of emission permits in the EU trading scheme (23€/tonne).

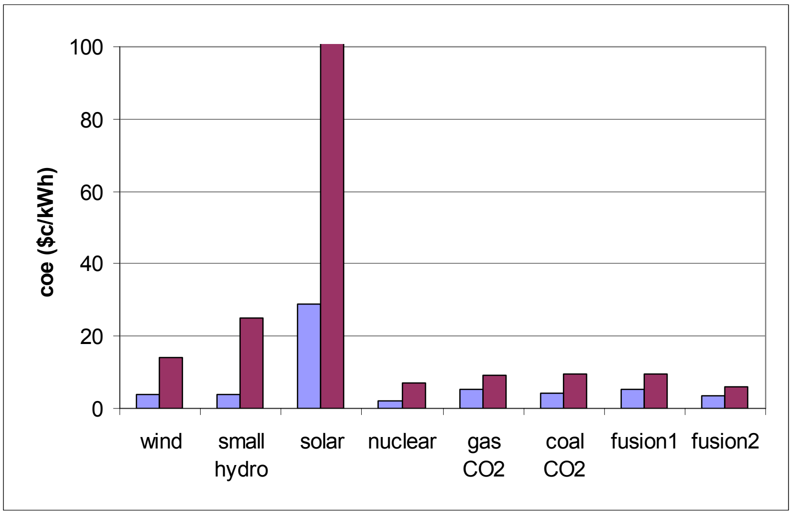

Figure 11: Comparison between electricity costs of other sources based on [9] with the fusion costs given here. The costs are in $cents rather than €cents. Fusion1 is the range derived for the first generation of plants; fusion2 is that based on further developments. Such a plot is speculative and cannot be used to determine which source will be the cheapest in the future. The only purpose is to set the background for fusion costs which appear reasonable in this context.

6. Conclusions

Although fusion is being developed as an energy source primarily for reasons of abundant fuels, safety and low environmental impact, it is important that we consider whether it can also be economically viable in a future energy market.

A power plant closely based around ITER design basis assumptions would be cost competitive with some energy sources being introduced in some markets but would not be expected to compete widely, although the developments needed to bring the economics into the right range are not very great.

A range of power plant concepts (PPCS Models A to D) have been studied in the EU, designed to capture the range of possibilities for a future power plant. This range links to ITER at one end (Model A) and extends to the best foreseen outcome (Model D), although the latter is not considered here as a first generation power plant.

The systems studies of these plants emphasise strongly the importance of the coupling between divertor heat load, radiation and current drive power. This has been studied here with a systems code (PROCESS) but merits much more detailed consideration with more sophisticated modelling of each aspect. The PPCS models range from large devices with high current drive power to more advanced concepts, smaller in size with low current drive power.

The economic assessments suggest that first generation power plants, if successfully brought into reliable operation, could be economically viable in a future energy market, particularly one in which the environmental impact of other systems is included, as is already happening with the carbon emissions trading scheme in the EU. Further developments of fusion, either to a more advanced plant or through high degrees of technological learning, could, if successful, produce highly competitive systems.

7. Acknowledgements

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8. References

[1] UK DEPARTMENT OF TRADE AND INDUSTRY, Energy Quarterly March 2004
[2] RWE Interim Report, January-March 2005
[3] HENDER, T.C. et al, Fusion Technology 30 (1996)
[4] UCKAN, N. and ITER Physics Group, ITER Physics Design Guidelines, Fusion Technology 19 (1991) 1493
[5] Final Report of the ITER EDA (ITER Documentation Series No 21, IAEA, Vienna 2001.)
[6] COOK I., Economic, Safety and Environmental Properties of Commercial Fusion Power, Paper KN1-SESE, This Conference
[7] MAISONNIER, D. et, "The European Power Plant conceptual Study", Proceedings of Symposium on Fusion Technology, Venice, September 2004, accepted for publication in Fusion Engineering and Design.
[8] WARD, D.J. et al, The Economic Viability of Fusion Power, Symposium on Fusion Technology, Venice (2004) to be published in Fusion Engineering and Design.
[9] INTERNATIONAL ENERGY AGENCY, Projected Costs of Generating Electricity, 2005 Update, OECD/IEA (Paris) 2005, ISBN 92-64-00826-8