The Impact of Physics Assumptions on Fusion Economics

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Abstract.
The development of fusion promises a long term supply of energy with widespread resources and good safety and environmental properties. However the introduction of fusion into the future energy market will rely on the development of an economically viable fusion power plant. Although predictions of the likely cost of electricity produced by a future fusion power plant are uncertain, it is important that an assessment is made to ensure that the likely economics are not unreasonable. In this paper the impact of different physics (and other) constraints on the economics of fusion is considered. Comparison with the expected future cost of electricity from other sources must take account of the trends in the energy market, particularly at present towards sources with low external costs related to impact on human health and the natural environment. Although these costs depend on the country concerned, a range of expected future costs can be derived. Comparison with the expected range of fusion costs shows that fusion can contribute to the future energy market.

1. Introduction

There is a large body of work on the projected economics of fusion power [e.g. 1-5]. Although there has been consideration of systems other than conventional aspect ratio tokamaks, with potential benefits, these will not be the focus of attention here. Rather the most well studied fusion device, the conventional aspect ratio tokamak, is considered.

The projected cost of electricity from a future fusion power plant is estimated using a systems code, PROCESS [5], which contains simplified models of each of the systems in a power plant. The plasma is modelled using expressions for the physics such as confinement, limiting density, limiting β, current drive efficiency, divertor behaviour, fusion power, fast particles etc. The magnetic field coils are modelled accounting for the superconducting properties and stresses. All other systems, such as the blanket and power conversion systems, are modelled in a more simplified way. Costing algorithms are based on a combination of industrial experience and ITER costings. Having specified the key constraints, such as normalised β, permitted coil stresses, unit size etc. the code searches for a power plant design that minimises the cost of electricity subject to the imposed constraints. Although such modelling contains intrinsic uncertainties, it is a powerful way of determining the impact that different assumptions make on the cost of electricity and consequently highlighting the areas that should be concentrated on in looking for advances towards reduced cost of electricity.

In addition to the physics and technology constraints that are applied to the power plant, the derivation of cost of electricity requires economic assumptions. Most important is the discount rate: a range of 5-10% is typical. Two other important factors are the unit size and the cost reduction due to series production. Fusion shows substantial economic benefits from larger unit size plant as will be discussed later. Costs of a component reduce as more of them are made, typically with each doubling of production reducing unit costs by 10-20%. In the following section, an overview of fusion economics based on this approach is given, before breaking down the importance of different parameters in the following sections.

2. Overview

In order to summarise the range of work on fusion economics, calculations are carried out which allows for a range of assumptions. These are shown in Table 1 which shows the ranges of assumed values of economic, physics and technology parameters. To illustrate the overall range of cost of electricity expected from fusion power, a probability distribution is ascribed to each parameter and then, using Latin hypercube sampling, a probability distribution of the cost of electricity is derived by running the systems code under each set of assumptions. In this analysis the economic parameters were assumed to be uniformly distributed between the maximum and minimum values. The probability distributions for the physics and technology parameters were assumed to be triangular, peaked at the mean values. This approach finds neither the most optimistic case (in which strong progress in each area is combined with the most favourable economic assumptions) nor the most pessimistic case (in which readily achievable performance is combined with the most pessimistic economic assumptions) as both of these are assumed to have a probability of zero. Rather an attempt is made to look for the likely cost of electricity. As usual, this approach is only as good as its assumptions, here of the probability distributions, however it serves to illustrate the range of cost of electricity that may be expected from a future fusion power plant.

Variable	**Minimum**	**Mean**	**Maximum**
Discount Rate (%)	5	7.5	10
10^{th} of a kind factor	.5	.6	.7
Unit Size (GW)	1	1.7	2.5
β_N	2.5	4	5.5
Limiting density n/n_G	0.7	1	1.4
η_{th}	0.35	0.48	0.6
Availability	0.6	0.7	0.8

Table 1: Range of assumptions used in deriving range of fusion cost of electricity.

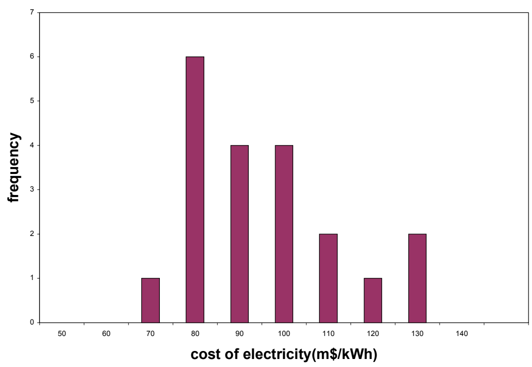

Figure 1: Resulting frequency distribution of projected cost of fusion electricity (1996$).

In this analysis, the range of cost of electricity is from 70-130 m$/kWh with the probability skewed towards the lower end. Note that the most optimistic set of assumptions, which results in a case not included here because of the assumed probability distributions, yields a cost of electricity approximately half of the lowest value in figure 1. This is a target that fusion should aspire to although we will see in the next section that it is not expected that future energy costs will require such progress before fusion can be introduced into the energy market.

3. Other Sources

To provide a comparison for fusion, two options are considered here, motivated by the present trends in the electricity market, although it must be noted that these trends vary widely across the world. By far the largest fossil fuel resource is coal, so we consider clean coal in which, rather than accepting the present high external costs [6], the technology is improved to reduce substantially the levels of pollution, including CO_2. Although this technology is not yet in place, it is estimated that this procedure would approximately double electricity prices from coal to lie in the range 60-120 m$/kWh [7,8]. From a Northern European perspective, a good option for renewable energy is wind power. Considerable progress has been made leading to costs of wind turbines around $1 per peak Watt$_e$, although the low load factor due to the intermittent nature of wind, leads to a cost around $3/W$_e$ (sent out). The intermittent nature of wind power would be unacceptable if wind were to contribute substantially to a nation's electricity supply, and energy storage would be necessary that would approximately double capital costs, leading to cost of baseload electricity in the range 80-300 m$/kWh, depending on the site, required energy storage times and storage costs.

It can be seen that the fusion costs derived above lie in a similar range to these other projected costs of the future energy market, derived on a similar basis, even without assuming an optimistic combination of advances in all areas.

4. Where Does Main Potential for Gains Lie?

In Section 2 the benefits to be gained from advances in each parameter depend both on the sensitivity of the cost of electricity to that parameter and the possible variation envisaged. Although the use of a low discount rate is very beneficial, this is outside our control so we will not consider it further. The next most important parameter in Table 1 is the unit size – fusion economics benefits substantially from increased unit size and there is quite an uncertainty over what unit size will be considered acceptable in future electricity markets, depending both on the country and future developments. The normalised β, thermodynamic efficiency and density limit then all impact to a similar degree (the latter partly because a wide possible range was assumed). Finally the least important here are the tenth of a kind factor (due to series production) and the availability – although it must be emphasised that these are only the least important because the range assumed for these parameters was the smallest.

To give an insight into the dependence of the cost of electricity on the different assumptions and constraints, we can treat the result of the Latin hypercube sampling of the probability distributions as experimental data, and derive a scaling law for the cost of electricity. Here, for the purposes of illustration we will express the result as a power law, although with capital costs, fuel costs and costs of replacement items, a more complex form should really be used. Figure 2 shows the result of this power law analysis and Eqn. 1 illustrates the strength of influence of the different parameters on the cost of electricity.

The implied power law scaling of cost of electricity is

$$coe \propto \left(\frac{DF}{A}\right)^{0.6} \frac{1}{\eta_{th}^{\;0.5}} \frac{1}{P_e^{\;0.4}\beta_N^{\;0.4}N^{0.3}} \qquad (1)$$

where D is the discount rate, F the 10th of a kind factor, A the availability, η_{th} is the thermodynamic efficiency, P_e the unit size, and N the normalised density. The exponents are only quoted to one significant figure to avoid the implication of an accuracy that is not warranted. These rounded figures were also used in drawing figure 2 (which partly accounts for the points that are inaccurately fitted). Apart from the economic variables, the order of merit of variables which reduce the cost of electricity is: availability; thermodynamic efficiency; unit size; normalised β, and limiting density.

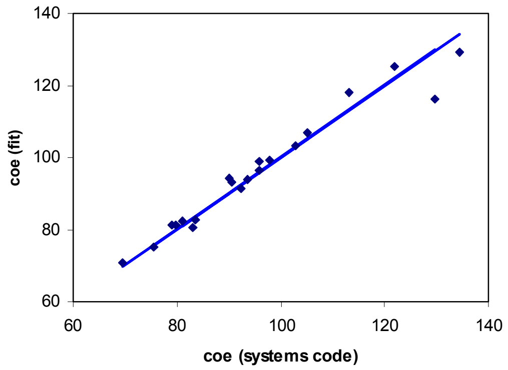

Figure 2: Scaling of cost of electricity with parameters.

5. Other Issues

One aspect that has not been described so far is the impact of current drive power. Each of the cases studied here assumed steady state operation with high energy NBI, with the current drive efficiency calculated. In each case the efficiency was sufficient to maintain that fraction of the current not driven by the bootstrap effect, without requiring excessive recirculating power. If this level of current drive efficiency is not attained in practise, the recirculating power would increase and could require a change in machine design – in particular to higher safety factor to increase the bootstrap current. This difficulty would be alleviated if higher β_N were achieved since high bootstrap current is then more easily achieved.

An issue that can have significant impact on power plant design is the tolerable divertor heat load. If only a low value (<10MW/m^2) were tolerable, the power-plant must either operate at reduced power density or use radiation to dissipate much of the power leaving the plasma, combined perhaps with an increased size to give a higher confinement margin. In either case, the cost of electricity will be increased. Depending on the details of how this is achieved, the cost increase is typically in the range 0-10%.

Although the availability was treated in the above analysis as an input, it is important to consider the constraints that achieving high availability may impose. As an example, the neutron wall loads in the cases looked at above lie in the range 2-3 MW/m^2, however this may be constrained to lower values by availability issues. For instance if it were necessary to achieve a lifetime for the blanket of 10 years (for availability or occupational radiation exposure reasons), then a blanket that could tolerate a fluence of typically 15MWa/m^2 would restrict the neutron wall load to 2 MW/m^2 (assuming 75% availability).

6. What Physics Progress Has Been Made?

Because there is no existing fusion power plant actually producing electricity, this question must be answered in an indirect way. One approach is to look at the variation in peak fusion power that experimental devices can produce compared to their capital cost. Although one-off experimental devices are likely to be very expensive, this at least allows us to see what progress has been made. Figure 3 shows a plot of capital cost per fusion watt against the fusion power of the experimental device. Only limited data is included and the figure relies on calculation and projection, most notably for the ITER designs. However the figure illustrates the positive development that, as fusion heads towards the GW range of powers, the capital cost of the basic machines moves towards the zone of 1$/W, as it must to become economical. Series production and advances in physics and technology will reduce the capital costs for a power plant compared to a one-off experimental device, however requirements for power production, high availability and steady state operation will add to the costs. The balance of these developments cannot be inferred from the diagram, but has been estimated in Section 2.

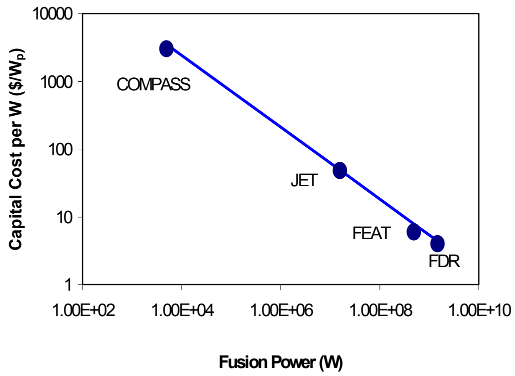

Figure 3: Illustration of the rapid fall in capital cost per fusion Watt as the size of fusion experiments increases.

7. Conclusions

Although it is fusion's widespread resources and safety and environmental advantages that chiefly argue for its development, economic assessments must be carried out to determine whether fusion can be competitive in the future energy market.

The main parameters that will impact on fusion economics are identified and probable ranges of these parameters are used in systems analysis to determine the probable range of fusion cost of baseload electricity. This is shown to be at a level expected to be acceptable in a future energy market where external costs have been internalised. By combining developments in all areas, it is possible to achieve costs that are substantially lower – this should remain the goal for fusion, even though it may not be necessary given the present trends in the energy market.

8. References

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9. Acknowledgements

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