Direct Cost of Electricity from Fusion Power Plants

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Introduction
The contribution that fusion power might make to the future energy economy depends on many factors. The ability of existing sources to meet future energy requirements safely, without generating excessive climate-changing emissions or other pollution, or a waste burden for future generations, must be assessed, as must the straightforward cost of electricity generated by a fusion power plant. Fusion would play a major role in the world economy if it produced competitive electricity, or if further exploitation of other sources became unfeasible due to resource restrictions or environmental or safety concerns. In this paper, only the predicted cost of electricity and its variation with assumptions is discussed. The contribution of 'externalities' to the energy debate is discussed in [1].

Optimisation of the economics of a conceptual power plant involves complex interactions between engineering and physics constraints and is carried out using systems codes that include parameterised models of all major systems [2,3,4,5]. It is nonetheless possible to obtain a simple understanding of the impact that physics constraints have on fusion economics and this is discussed here.

Physics of Fusion Economics
The required thickness of the structure comprising the first wall, blanket, shield and magnetic coils is approximately constant so the material volume of the fusion plant is most strongly dependent on the surface area of the first wall. Since the benefit of the device is the power output, the economics is determined by the ratio of power to cost. A high wall load machine would be generally expected to produce the most economic electricity if it were not for the issue of recirculating power.

In practice, the optimum value of wall load in a power plant can be determined either by technological or physics constraints. The physics constraints include the limiting value of β that can be achieved, limiting the fusion power that can be produced, and the efficiency of current drive. In a steady state tokamak, the power required for current drive can cancel out the gains of increasing wall load by reducing the machine size. To illustrate the physics constraints, a simple model of the economic efficiency is given here.

The economic efficiency increases roughly with the figure of merit, M, defined as

$M = \dfrac{P_{fus} - P_{rec}}{a^2}$, where the benefit of the machine is the fusion power minus the

recirculating power, whilst the cost of the machine is assumed to scale primarily with the square of the minor radius (assuming fixed geometry).

The recirculating power, required to sustain the plasma current in a steady state tokamak is given by $P_{rec} \propto \dfrac{nIR}{\eta_{CD}}(1 - f_{BS})$, where the power required for current drive increases with density, current and size, and is reduced by high current drive efficiency, η_{CD}, and by the fraction of current carried by the bootstrap effect, f_{BS}. The thermal fusion power varies like $\beta^2 B^4 a^3$ leading to a variation of the figure of merit

$$M = C_1 \beta^2 a - \left| C_2 \frac{\beta}{q}(1 - f_{BS}) \right| \tag{1}$$

where the magnetic field, plasma temperature and current drive efficiency have been assumed constant. The absolute value of the second term is taken, in order to penalise the plant for producing too much bootstrap current as well as too little.

It is clear that since the fusion power increases faster with β than does the recirculating power, it is desirable to operate at as high a value of β as possible. In general this will be at (or above) the Troyon limit, where β scales inversely with q, requiring a power plant to operate at low q, the limiting value set by disruption avoidance. There are exceptions to this low q rule, however, in small devices or with less efficient current drive, in which case the recirculating power must be minimised by operating with high bootstrap fraction, at higher values of q. High bootstrap current is also a natural feature of power plants operating at high normalised β, β_N.

To illustrate how the recirculating power can lead to an optimum value of wall load, consider a power plant producing a **fixed** fusion power. Changing the wall load (L_w) represents changing the machine size ($a \propto 1/L_w^{1/2}$), so the value of β must change to maintain the same fusion power ($\beta \propto L_w^{3/4}$). Assuming operation at fixed β_N, the safety factor will also vary ($q \propto 1/L_w^{3/4}$). Rewriting equation (1) in terms of wall load gives

$$M = C_3 L_w - C_4 L_w^{3/2}(1 - f_{BS}) \tag{2}$$

The main result of this analysis is that the figure of merit increases with wall load up to a maximum, then falls as the recirculating power becomes an increasingly important fraction of the fusion power. The economic efficiency goes to zero when all the power produced is required to sustain the plasma current. Although it is possible also to parameterise the bootstrap fraction, that is not done here to avoid complexity. The main result is not influenced substantially by the variation of bootstrap fraction with wall load.

Equation (2) shows one physics limitation to the wall load, unrelated to technological constraints, resulting from the current drive power. There was another limit implicit in the derivation of equation (2), since as the wall load increased the value of q fell and in fact reached a value below which the disruption frequency would increase unacceptably.

In that case it is q, rather than the recirculating power, that would set the limit to the wall load.

Impact of Unit Size
Another important result from equation (1) is that a higher fusion power machine is more economic. This is primarily because, as the size of the plant increases, the fusion power increases faster than either the cost of the machine or the recirculating power. In addition there are further economies of scale in systems code analysis which lead to an overall cost of electricity that varies as $1/P^{0.4}$ [5].

Limiting β
The fusion power that can be achieved in a given machine is limited by the achievable value of plasma pressure. Assuming the β to be a fixed fraction of the Troyon limit, then an increase in the value of normalised β, β_N, that can be achieved leads to more efficient use of the plant and reduced cost of electricity. As with the unit size, the systems code analysis gives a cost of electricity that varies as $1/\beta_N^{0.4}$ [5]. This is a less strong scaling than simple analysis would suggest because some of the benefits of higher β are offset by a reduction in the magnetic field that result from reduced machine size. Figure 1 illustrates the variation of cost of electricity with the product of normalised β and electrical output, $\beta_N P_e$ (GW$_e$).
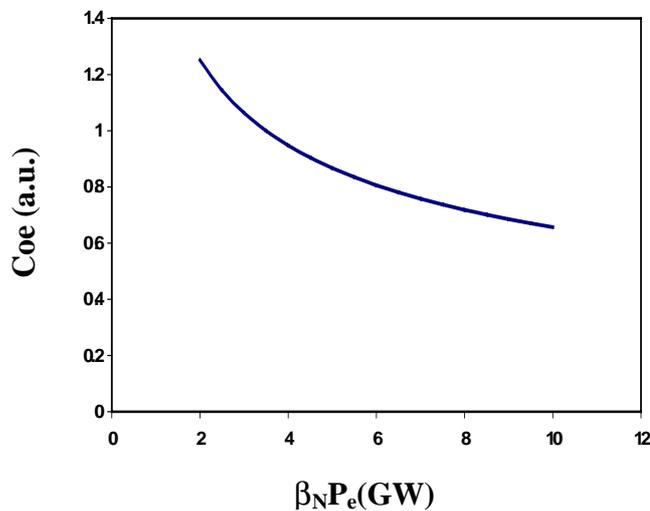
Fig.1: The cost of electricity falls as either β_N or unit size is increased. Increasing the product $\beta_N P_e$ by a factor of 3 reduces the cost of electricity by 35%.

Although the main impact of cost is from the β that can be achieved and the unit size, the peaking of the profiles, particularly the density profile, also has a significant effect. Improvements in superconducting technology that allow an increase in magnetic field at the coils without a large cost penalty would also have a strong effect on the cost of electricity.

Breakdown of Costs

The analysis of cost of electricity from systems code analysis gives interesting insights into the different contributions to the cost of electricity. It is often stated that the costs of a fusion plant are dominated by the capital cost of constructing the plant. In fact, the costs of consumable items, particularly the divertor and blanket structures, can represent a considerable part of the cost of electricity. A typical breakdown of costs is 40% from the cost of the fusion specific capital (excluding consumables), 40% from operation and consumables (divertor, blanket, first wall and fuel) and 20% from the non fusion specific plant [5]. This varies according to the length of shutdowns required to change the divertor and blanket structures. If these become long, then the machine design evolves towards a more capital intensive machine requiring fewer interventions. This provides another limit to the wall load, that of maintaining a high machine availability.

Cost of Electricity

The purpose of this paper is primarily to elucidate the physics constraints that impact on the cost of electricity. However it is inevitably of interest to come up with a prediction for the cost of electricity. It is usual to make a range of assumptions and determine a corresponding range of cost of electricity. Assuming the product $\beta_N P_e$ varies from 3.5 up to 10, the upper limit resulting from advances in physics and growth in the unit size as the electricity supply industry expands, the cost of electricity from a tenth of a kind plant is in the range of 120-70 mECU/kWh (in 1990 ECUs) [5]. At the lower end of the range the costs are comparable to predicted costs from other sources. At the upper end of the range, it is anticipated that fusion would only be introduced in the event of restriction of use of other sources for reasons of resource limits or environmental protection [6].

Conclusions

The impact of physics assumptions on the economics of fusion have been briefly described and the ways that fusion economics can be substantially improved by increased β limits or, more simply, by increased unit size discussed. With reasonable assumptions it appears that fusion could make a contribution to the future energy market. Discussion has concentrated on conventional aspect ratio tokamaks, and the possible advantages of stellarators, with no current drive requirements, and tight aspect ratio tokamaks, with higher achievable β, have not been addressed here.

References
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