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THE ECONOMIC VIABILITY OF FUSION POWER

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Abstract

Although fusion power is being developed because of its large resource base, low environmental impact and high levels of intrinsic safety, it is important to investigate the economics of a future fusion power plant to check that the electricity produced will, in fact, have a market.

The direct cost of electricity of a fusion power plant and its key dependencies on the physics and technology assumptions, are calculated, as are the materials requirements. The other important aspect of costs, the external costs which can arise from effects such as pollution, accidents and waste are also given.

Fusion is found to offer the prospect of a new energy source with acceptable direct costs and very low external costs. This places fusion in a strong position in a future energy market, especially one in which environmental constraints become increasingly important.

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1. Cost of electricity methodology

The following results are derived using a systems code, PROCESS [1], to produce consistent models of conceptual power plants and, using costing algorithms validated against existing machines as well as ITER costs, to determine the capital costs, operation and maintenance costs, fuel costs, cost of replaceable components and decommissioning costs. These are used to determine the levelised cost of electricity [2]

$$\text{coe} = \frac{\sum_t (C_t + \text{OM}_t + F_t + R_t + D_t)(1+r)^{-t}}{\sum_t E_t(1+r)^{-t}} \quad (1)$$

where the capital, C , operation and maintenance, OM , fuel, F , replaceable components, R , and decommissioning costs, D , as well as the income stream from electricity sales, are discounted back to the start of operation with a discount rate r . The cost of electricity, coe , is determined by equating the total discounted costs to the total discounted income stream.

2. Economics of a conservative plant

In this introductory section, we consider the economic viability of a fusion power plant based around the parameters of the ITER design [3], developed into a power plant. In particular, a value of normalised β (β_N) of 1.7 and moderate values of H -factor, density and divertor heat load are used [3]. Experience of costing power plants would tell us that such a plant is not optimal to produce economical electricity, but it

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is instructive to study what could actually be achieved, as well as looking at possible improvements starting from ITER parameters as a base case.

Figure 1 shows a summary of the cost of electricity of an ITER-like plant, with the evolution to a more developed plant which achieves a higher β_N , 3.4. The figure shows how costs will vary with learning factor, that is the reduction in cost that is achieved in moving from a first-of-a-kind plant through to a mature technology [4]. For comparison, the costs of wind power and solar photovoltaic (PV) are also shown (PV for UK) both with and without an allowance for storage costs which would be required to supply firm, reliable power. Again the costs are shown against learning factor, with the learning factor of 1 being applied to the first 1GW of power in each case. In these terms, wind power has already progressed to learning factors below 0.5, having reached world capacity of approximately 40GW, so these data are historical rather than projections for wind.

The comparison shows that although fusion power based on ITER parameters would not be expected to be economically optimum, it would be expected to have a cost advantage over PV and would be comparable to wind power if storage were necessary to provide firm power. If the fusion plant can advance to β_N of 3.4, typical of values that have been achieved in existing experiments, then fusion costs would be comparable to wind power even without allowing for energy storage. This comparison applies at the same level of technology maturity: a technology that has already matured will, of course, have an advantage over a new technology. This will be discussed further later.

3. A broader perspective

A power plant based closely around ITER parameters is probably not the most likely outcome of the fusion programme. The fusion programme will certainly progress over the next decades, as it has done in the past, and we need to consider what a power plant may look like in the light of expected or possible progress. This is not to suggest that ITER is unambitious; the operation of a fusion machine dominated for the first time by high levels of fusion power with the need for very high power handling is a great challenge and a crucial step forward in the fusion programme. Nonetheless, assuming this is successful, we need to see what the implications of progress are and where progress is most beneficial in improving the economic case for fusion.

Figure 1 showed that a power plant based on an improved, mature, version of ITER may well offer economical electricity, at electricity costs in the range 5 to 10 €cents per kWh, which could already be competitive in many countries and will probably be more competitive in a future electricity market as environmental constraints tighten. Here we will consider how the cost of electricity can best be reduced.

To elucidate the variation of cost of electricity with plant parameters, ranges of key parameters have been used to produce a range of fusion power plant models.

These have then been used to determine the variation of cost of electricity with the main parameters [5]. The resulting cost of electricity scaling is given as

$$\text{coe} \propto \left(\frac{rF}{A} \right)^{0.6} \frac{1}{\eta_{\text{th}}^{0.5}} \frac{1}{P_e^{0.4} \beta_N^{0.4} N^{0.3}} \quad (2)$$

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and the agreement between this scaling and the actual results is shown in Figure 2. r is the discount rate, F the learning factor, A the plant availability, η_{th} the thermodynamic efficiency, P_e the unit size, β_N the normalised β and N the multiplier of the density compared to the density limit scaling. Apart from the discount rate, the order of merit for improving economic efficiency is technological learning, availability, thermodynamic efficiency, unit size, normalised β and limiting density.

There is an additional important effect, not included in Equation 2, that involves the interaction between divertor heat load limit, current drive power and confinement. This interaction is a crucial one for ITER to establish and has been studied here in only a limited number of specific cases. To look at these dependencies, and to clarify the actual value of cost of electricity, we can turn to more detailed studies which have been carried out under the European Power Plant Conceptual Study (PPCS) [6].

In the PPCS a range of 4 plant concepts has been studied, as point designs that cover the range of the more general studies represented in Figure 2. These range from a steel based, water cooled plant (Model A) through to an advanced system using SiC/SiC as a blanket material and self-cooling with a lithium-lead eutectic (Model D). These concepts are intended to cover the range of possible fusion power plants, linking to ITER at one end through to highly advanced power plants at the other end. Details and references for the plant design parameters and the key physics issues can be found in [6].

Figure 3 shows the cost range for these design points. Depending on the level of technological and scientific advance and the level of maturity, the cost range for

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fusion in this study is 3 to 10 €/kWh. This broad range arises because of the combination of level of advance over ITER and level of technological maturity. It is clear that these fusion costs have a reasonable chance of being competitive in a future energy market.

4. Materials

A crucial issue for fusion is the development and demonstration of materials that will tolerate the fusion environment for sufficiently long that the plant can run with a reasonably high availability. There are good candidates, not least the low activation martensitic steels that now exist and have been exposed to, and tolerated, neutron irradiation in fission plants [7]. There are strong economic implications of the materials properties, in particular their lifetimes, and these areas must be investigated as a priority. The most important areas of the plant are those in close proximity to the fusion plasma itself, most notably the first wall, blanket and divertor; here we will look primarily at the blanket materials and the need for blanket replacement.

Figure 4 shows the variation of plant availability and corresponding cost of electricity for a fixed design of power plant in which the total neutron fluence that the blanket materials can tolerate is varied. A higher blanket fluence leads to a longer blanket lifetime and a higher availability, with correspondingly lower cost of electricity. It is clear from this figure that a blanket fluence of more than 5 MWa/m² is essential, 10 to 20 is desirable, but higher values have diminishing benefit as the blanket replacement has a diminishing impact on the machine availability. This is because the plant must in any case be taken out of operation for other reasons, such as divertor replacement.

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Similar calculations have been carried out for divertor replacements showing that it is strongly desirable to reach a divertor lifetime of around 2 full power years.

5. External costs

The external costs of an energy system are those related to impacts on health, the environment etc that are not captured in the direct costs paid by the consumer. The assessment of such costs has been formalised in a methodology known as ExternE [8] which, whilst developed for existing energy systems, has been extended to assess the external costs of fusion power plant concepts. To ensure consistency, the assessment of fusion has been carried out by people who also carried out the assessment of other energy sources.

The ExternE methodology is a bottom-up methodology, with a site-specific approach, that is, it considers the effects of an additional fuel cycle located in a specific place. Quantification of impacts is achieved through the damage function, or impact pathway approach. This is a series of logical steps, which trace the impact from the activity that creates it to the damage it produces, independently for each impact and activity considered.

This methodology was the one applied to the assessment of the external costs of several models of a fusion power plant in the Socio-Economic Research in Fusion (SERF) and the Power Plant Conceptual Study programmes. In these analyses of externalities, the effect of selecting different structural materials and other technological options on the external costs of fusion power plants were investigated. In each case the external costs are found to be very low, for instance in the studies of

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the PPCS plant models with the highest external costs, these were 0.09 €/kWh for Model A and 0.07 €/kWh for Model B. Plant models using more advanced designs and materials have even lower external costs.

These estimations of external costs were compared with the external costs calculated for other energy technologies taken into account whenever possible the technological advances that could be achieved by conventional and renewable technologies, such as carbon sequestration in fossil technologies, in 50 years time. The large values of external costs from conventional energy technologies such as coal fired power plants are dominated by the atmospheric pollution both of CO₂ and of chemicals more directly harmful to human health, including SO₂ and NO_x. There are large uncertainties in the cost assessment of these areas but it is clear that fusion, along with most renewables, does not contribute significantly to atmospheric pollution. This is the main reason for the results shown in Figure 5 that fusion belongs to the group of energy technologies with low external costs [9].

6. Fusion's role in a de-regulated energy market

We have seen that a mature fusion technology, if successfully developed, is likely to be economically competitive. As with other new energy systems, the difficulty in adoption into the energy market is most likely to arise in early generations of power plants, which will not yet have reached maturity. There are two main drivers likely to overcome this. The first is the wide geographical variation of electricity prices, varying by around a factor of 4 around the world [10]. This means that fusion is likely to find a role in some parts of the world before others, develop as a mature technology and then become more widespread as costs fall. The other is the large amount of

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regulation and incentives that exist in a competitive (de-regulated) market, introduced to achieve goals of environmental protection, energy supply security etc which would not otherwise be achieved in an entirely free market. Examples include feed-in tariffs, obligations to include non-fossil fuel options and carbon taxation or permits. These pressures on the market look likely to increase rather than decrease and effectively place a value on the environmental advantages of fusion over some of the main energy alternatives. If this process continues this will also enable fusion to be introduced and will serve to promote the development through its early implementation, as is presently happening with other energy systems such as wind power.

7. Economics of fusion development

Studies have been carried out of the value of developing fusion [11]. These studies use probabilistic decision analysis to examine the development and exploitation path of fusion, including probabilities of failure at each stage. The costs of development and the benefits of a new major energy systems are then discounted to give a Net Present Value (NPV) of the fusion programme. This process depends on the assumptions made of course, particularly on the assumptions about future electricity prices and the probability of successful development of fusion power. Here, the broad conclusions are described.

The main result is that with reasonable assumptions, the fusion development programme gives a substantial positive NPV. This primarily arises because the size of the annual world electricity market dwarfs the annual expenditure on fusion development, presently by a factor of approximately 1,000. Even including the

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probability that fusion is not successfully developed as a commercially viable technology, and discounting the future benefit over the development period, the total benefit of future fusion energy supply remains far greater than the cost. A typical calculation gives a total discounted development cost in the range 10 to 20B\$ and the total discounted future benefit (with fusion capturing 10-20% of the electricity market in 50 years time) of 400 to 800B\$. Even including the probability of failure, the NPV remains in the range of 100-400B\$, suggesting that if fusion could capture 1% of the electricity market, its development would be worthwhile.

There are three additional important features of such calculations. A sufficiently high discount rate can, of course, reduce the NPV to a low level; a real discount rate of 15% would be required to do this, representing the fact that if we concentrate on a 5 to 10 year time horizon, then developing future energy systems is not of interest. A countervailing effect is the present drive of environmental concerns towards a radical shift in our energy supply systems. This is likely to drive the market towards higher costs and so increase the NPV, even assuming high discount rates. The third issue is the rate at which fusion development is pursued. If we were to use these techniques to maximise the NPV of fusion research, this would certainly lead to a speeding up of the development programme, balancing greater investment where necessary against earlier implementation of fusion. Figure 6 shows the results of a probabilistic decision calculation in which fusion development is accelerated by advancing each stage, but handling the increased risks of failure by greater investment to allow parallel exploitation of more facilities. Although only illustrative, this calculation shows that up to a certain point, speeding up the fusion programme is beneficial, although a strongly aggressive development programme, in which DEMO, a demonstration

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power plant, is built early in ITER operation, has no benefit over a more measured, but still ambitious programme. This is because it is judged that the probability of this development strategy succeeding on such a fast time-scale is too low. Nonetheless, it appears that a Fast Track approach can potentially double the value of fusion development, if successful in advancing fusion implementation by around 15 years.

8. Conclusions

Although fusion power is being developed because of its large resource base, low environmental impact and high levels of intrinsic safety, it is important to investigate the economics of a future fusion power plant to check that the electricity produced will, in fact, have a market.

Taking a conservative power plant conceptual design, in which no advances over the basic ITER parameters are assumed, the cost of electricity is estimated to be lower than PV and comparable to wind (if storage is needed for firm power) at the same level of technological maturity. Advances in the physics that may well be achieved in ITER would lead to a power source competitive to wind without storage.

It is advantageous to look at where economic gain can be made in pushing for developments over the ITER operating point. Higher β_N , higher density operation are important but even more important are the effects of plant availability, unit size and thermodynamic efficiency. It is also important that a path to technological maturity that maximises the learning effects be considered at each stage. These developments beyond ITER have been explored in the PPCS in Europe and the results suggest a

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mature fusion technology could supply electricity in the range 3-7 €/kWh, likely to be competitive in the future energy market.

In examining the external costs associated with fusion power, it is found that fusion lies in the group of technologies with low external costs. This is primarily because of the low level of atmospheric pollution, including greenhouse gases.

The value of establishing fusion as an energy option has been investigated using a probabilistic decision analysis, discounting all costs and benefits to the present day and including the estimated probability of failure at each point of the development process. This shows a substantial positive value of the fusion programme, which remains positive even if the future contribution of fusion were constrained to be less than 1% of the electricity market. Studying how the value varies with the rate of development shows that around twice the value could be obtained by a Fast Track development, in spite of assuming increased annual development costs due to parallel exploitation of key devices.

Acknowledgements

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Figure captions:

Figure 1: Illustrating the range of cost development expected from an ITER-based fusion power plant compared to the development for wind and PV [4]. The fusion cost range is from $1.7 < \beta_N < 3.4$, the upper values for PV and wind allow for energy storage to provide firm power.

Figure 2: Scaling of cost of electricity with main parameters as given in Eqn 2.

Figure 3: Cost of electricity range as derived from the PPCS plant models A to D. Model A is close to the improved ITER values of Figure 2. Model D is an advanced plant with high thermodynamic efficiency and high physics performance (advanced tokamak).

Figure 4: Materials properties can substantially impact on the power plant availability and cost of electricity. Here the effect of the lifetime tolerable neutron fluence of blanket structural materials is given.

Figure 5: The external costs of advanced energy systems. The lower bars assume a low cost of global climate change. Fusion plants fall in the group of energy systems with low external costs.

Figure 6: The impact of speeding up fusion development on the value of fusion as an energy option. The increased value arises in spite of greater short term development costs.

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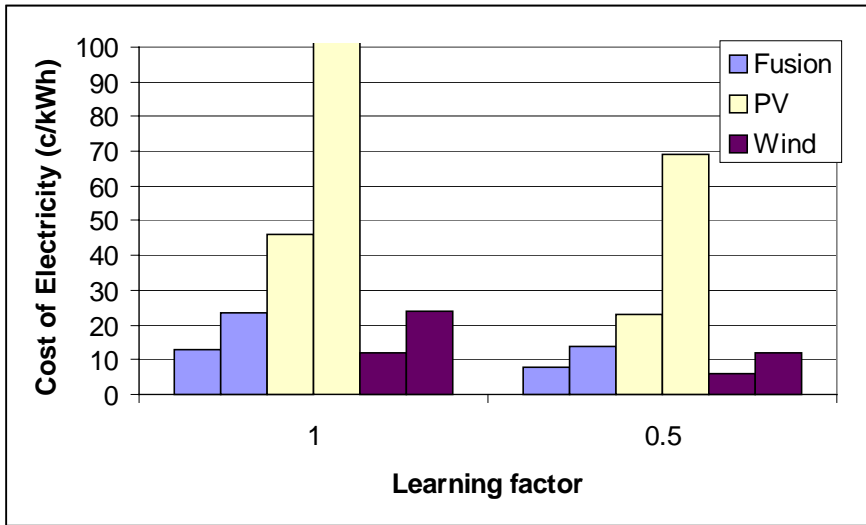


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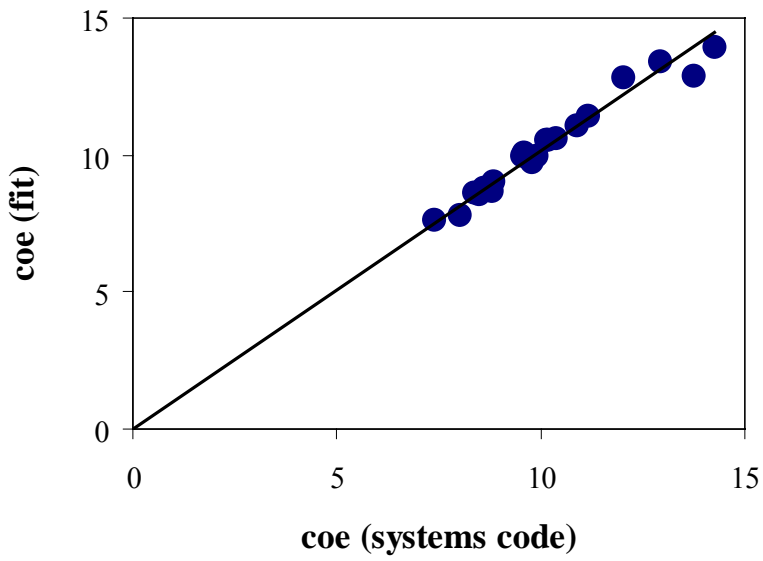


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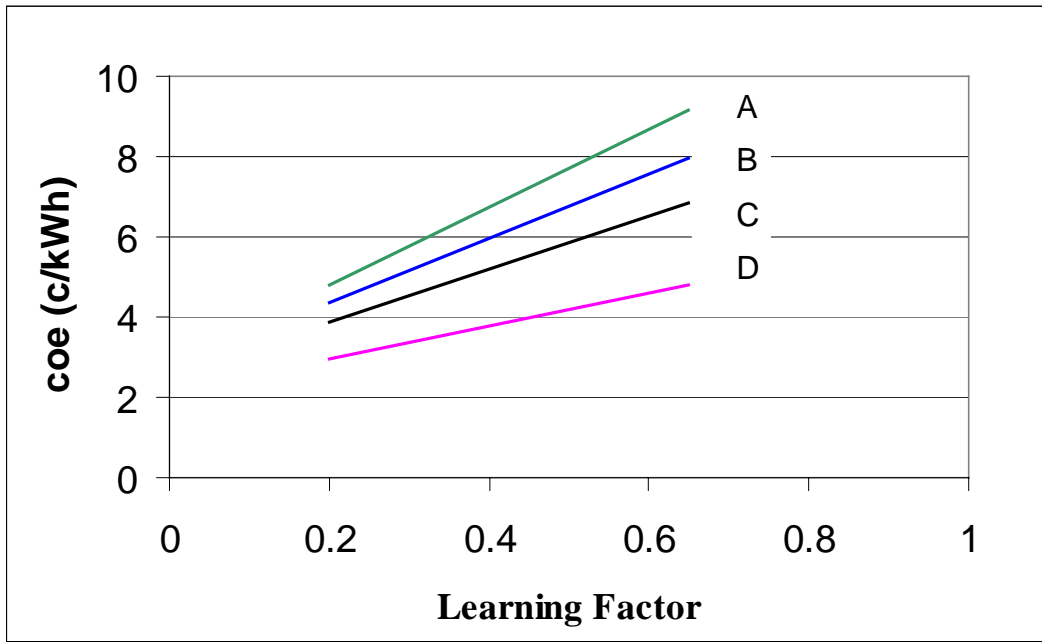


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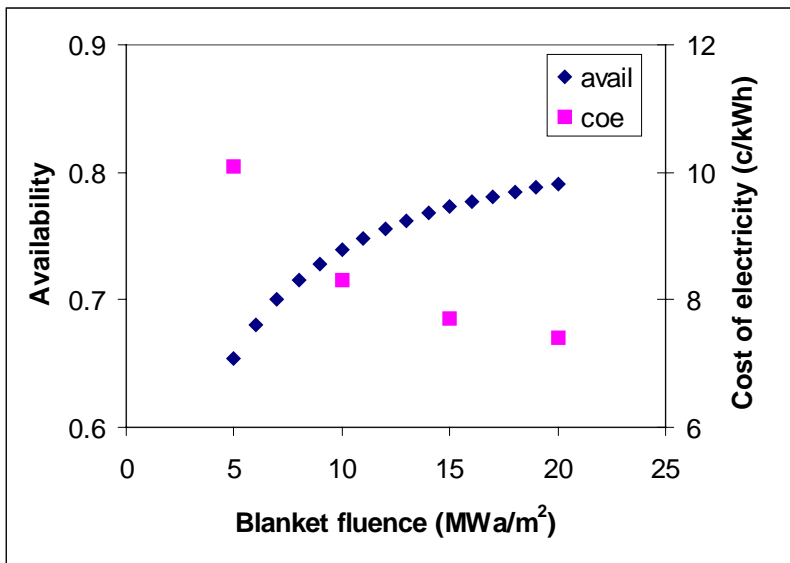


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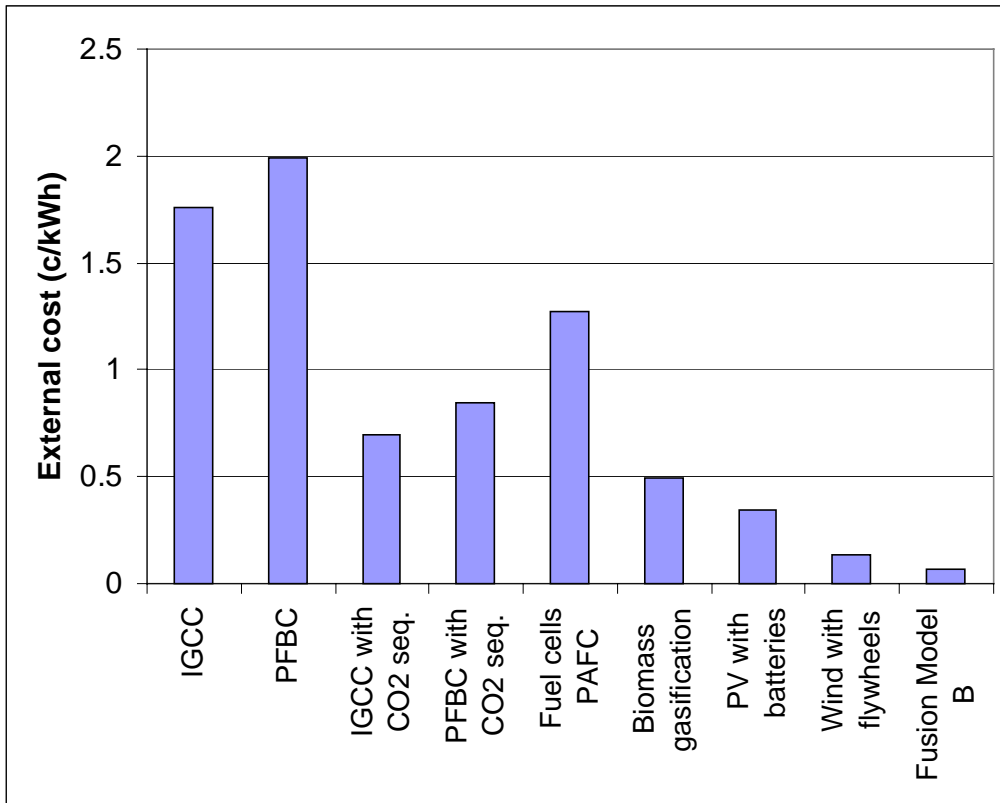


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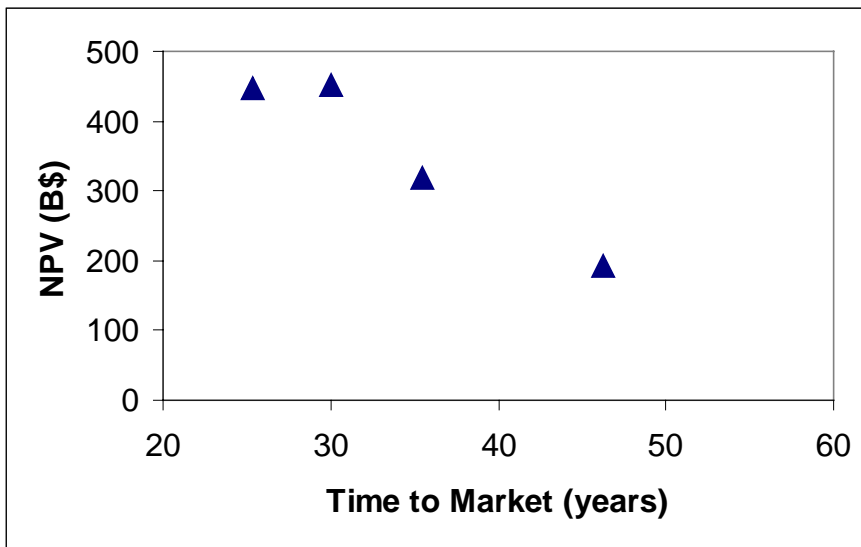


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