A method of (in)validating the projected levelized cost of electricity of fusion power

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Abstract

Reliable predictions of the cost of electricity from fusion power plants are fundamental to making sound investment decisions and efficiently allocating resources. Yet, without any detailed designs for fusion power plants, let alone any operational experience, how can we be sure that the projected costs of electricity that inform these decisions are achievable?

Rather than trying to project the levelized cost of electricity (LCOE), here we recast the problem and instead work backwards from an assumed LCOE to calculate the implied cost of fusion hardware. In so doing it is possible to invalidate some claimed LCOE projections. Furthermore, this approach helps to elucidate a fundamental shortcoming of fusion power plant schemes that rely on a thermodynamic cycle for power generation: their low *net* thermal efficiency. The low net thermal efficiency, caused by the power plant itself being a major consumer of electricity, results in a relatively high cost of electricity. The low net thermal efficiency also implies that, on a per megawatt hour basis, cooling water demand from fusion thermal power plants will be significantly higher than for conventional thermal power plants.

For fusion power to be widely adopted it will need to be economical. The economic implications of design decisions need to be widely understood early, lest ultimately uneconomical paths are followed. The easy-to-use methodology described herein can help researchers, even those unfamiliar with financial jargon or concepts, to understand how their design decisions may affect the financial viability of fusion power plant concepts.

Keywords

Levelized Cost of Electricity, LCOE, magnetised target fusion, power plant, economics

Statements and Declarations

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1. Introduction

Forecasting the cost of electricity for any power plant is challenging. This is all the more so for fusion power plants: a fusion power plant has never been built, let alone operated for decades. As such there is no recent operational experience to use as a basis, there are not even any detailed power plant designs. Yet, it is necessary to forecast the cost of electricity – after all if the electricity generated is too expensive there will be no buyers [1], there would be no reason to build such a power plant, and in turn no reason to invest in fusion to fund the necessary research and development in the first place.

To this end, we will use the levelized cost of electricity (LCOE). Historically, LCOE has been used for policymaking and assessing the cost competitiveness of technologies. LCOE indicates the economic costs of a generic technology, not the financial costs of a specific project in a specific market.

LCOE has shortcomings [2] and the immediate applicability of LCOE in today's electricity systems is limited. This is due to structural changes in demand and supply, in particular the advent of significant shares of variable renewables with zero short-run marginal costs, but also storage and distributed generation. In systems with large shares of variable renewables, costs must be assessed at the system rather than at the plant level. Nevertheless, despite its limitations LCOE remains a uniquely straightforward, transparent, and well understood metric [3].

The LCOE of different types of generation must be compared on a consistent basis, and such a comparison is outside the scope of the current article (see instead [3] for example). However, some indicative values of LCOE for different types of generation are useful for context and are provided in Table 1:

Nuclear	71 $/MWh	Geothermal	62 $/MWh
Combined cycle gas turbine	45 $/MWh	Solar PV	35 $/MWh
Wind offshore	66 $/MWh	Wind onshore	39 $/MWh

Table 1 – Indicative LCOE of different types of generation at a 7 % discount rate after [3]. In practice different types of generation would have different discount rates with lower risk projects having lower discount rates and vice versa.

It is not uncommon for estimates to be made of the LCOE of fusion power concepts. In general, the estimates are based on projections of the future cost of major components. This is done either by simple scaling arguments or through the use of more sophisticated codes such as PROCESS [4]. LCOE projections for fusion power plant concepts show a large range varying from 40-165 $/MWh [5]. This includes a 2018 analysis of a DEMO[1]

[1] DEMO refers to a proposed class of nuclear fusion experimental reactors that are intended to demonstrate the net production of electric power from nuclear fusion.

power plant with a predicted LCOE of 160 $/MWh for which it was suggested there was great scope for reducing investment costs on the basis of technological research and development and a high probability of it becoming the cheapest and cleanest energy source for an unlimited time [6]. A more recent estimate of the LCOE of a DEMO power plant was reported as 248 $/MWh [7]. Fusion power LCOE estimates vary in their methodologies and assumptions making it difficult to make comparisons. In some cases claims are made about competitive LCOEs without being substantiated [8,9].

When LCOE projections include cost reductions from 'learning' to yield so-called 'Nth of a kind' costs it is difficult to assess whether the result is realistic. In applying experience curves the first step should be to decompose the facility into subsections whose costs are likely to change at different rates for a given increment of new plant capacity [10]. For example, the novel heat source of a fusion power plant would be expected to benefit from learning at a different rate to steam turbo generators that have already undergone a century of development and optimisation. However, it is not always clear the extent to which this has been recognised (for example [11]) and thus whether the final result is plausible.

Fusion economics is not necessarily driven solely by electricity; power plants could also sell heat.

Process heat is complex to assess as consumer requirements vary widely, even within the same industry. Furthermore, consumers of industrial heat often require temperatures above 700°C [2] or they already use effectively free fuel that is a byproduct of their production process, consumers would likely need to be co-located with the fusion plant, and crucially the minimum unit size of the fusion plant (dictated by physics) may be larger than required by individual process consumers [1].

Waste heat – large quantities of low temperature heat found at turbine exit – are suitable for district heating. However, district heating has many barriers to adoption including, but not limited to, high initial investment, cheap fossil fuels, path dependency (it is expensive to switch from existing systems that have not reached end of life), unfavourable regulations, monopoly concerns, lack of coordinated policy, and short-term political cycles. Fusion does nothing to solve these problems and, were the problems to be solved, fusion would not be the only beneficiary – competing thermal power plants would also benefit. Indeed, only a small fraction of fission reactors provide district heating, and of those that do the average energy withdrawal is less than 5 % [12]. The small energy withdrawal is unlikely to significantly alter plant economics.

[2] Process heat temperatures may be challenging for fusion to provide due to temperature limitations of structural materials.

For simplicity in this study, we will neglect the potential for fusion power plants to sell heat.

In this article we recast the LCOE forecasting problem. Rather than forecast an LCOE we instead start with an LCOE and 'work backwards' eliminating known costs until all that remains is the unknown cost of fusion hardware. In so doing it is possible to show that some LCOE projections are unrealistic. This has practical significance for policymakers allocating research funds and for investors in the private fusion industry. The approach described herein can also help researchers make informed design decisions that are more likely to lead to an economical power plant.

This analysis re-emphasises a shortcoming of fusion power schemes that use neutrons to generate heat and drive a thermodynamic power generation cycle: the net thermal efficiency is inherently lower than for conventional thermal power plants because *the fusion power plant itself is a major consumer of electricity*. Consequently, the levelized cost of electricity is relatively high. Fusion power plants with higher thermal efficiency are required [13–15].

The method, outlined in section 2, is best illustrated by means of a worked example which is given in section 3.

2. Method

The levelized cost of electricity, LCOE, is simply the sum of lifetime costs divided by the sum of lifetime output:

$$LCOE = \frac{\Sigma\, costs}{\Sigma\, net\ output} \tag{1}$$

For a given LCOE and assumed plant output the total lifetime costs can therefore be calculated thus:

$$\Sigma\, costs = LCOE\ \times \Sigma\, net\ output \tag{2}$$

The lifetime costs can be broken down into various constituent parts: operation and maintenance costs, interest payments, indirect costs, direct costs of conventional hardware, and direct costs of fusion hardware. Reliable estimates are publicly available for all but the fusion hardware. Therefore, the known costs can be subtracted from the lifetime costs to yield an implied cost of fusion hardware. The implied cost of fusion hardware must be greater than zero – if not, the projected LCOE is unattainable.

In summary, the method proceeds as follows:

1. Use an assumed LCOE and equation (2) to calculate the lifetime costs.
2. Estimate operation and maintenance costs.
3. Calculate total capital costs.
    - The interest rate (so-called 'discount rate') is unknown, so it can be left as a free parameter.
4. Subtract the indirect costs.
5. Subtract the costs of conventional hardware (e.g., steam turbines, turbo generators, water cooling plant, ...).

The amount of money remaining is the amount that can be spent on fusion hardware. If this number is less than zero, the assumed LCOE is unattainable.

3. Worked example

We will use the conceptual design of a magnetised target fusion (MTF) power plant [16] as the basis of a worked example. This power plant concept is chosen as, in addition to design information, projected LCOEs of 50-65 $/MWh [9] and 64-73 $/MWh [17] are also available with which comparisons can be made.

The conceptual design produces a gross electrical output of 726 MW by operating two fusion reactor cores in tandem [16,17]. For the sake of the worked example, we will assume:

- Plant lifetime 40 years. This is comparable with conventional thermal power plants.
- Capacity factor 85 %.

For context, over the period 2014-2023 the capacity factor for nuclear plants in Canada was 77 %, in the UK was 71 % [18] and in the U.S. was 92.5 % [19]. The International Energy Agency assume a standard capacity factor of 85 % for nuclear fission in their analysis [3]. Adopting the capacity factor of a conventional nuclear power plant implies that a fusion power plant, with its additional complexity, can achieve similar levels of availability and utilisation. This may be overly optimistic [5], but as will become clear, this assumption can be readily changed and the analysis repeated.

The assumed plant lifetime and capacity factor imply a lifetime generation of 90 543 MWh.

Step 1: Lifetime costs

From equation (2) an LCOE of 50 $/MWh implies a lifetime cost of $4.5 B. The general result for a range of LCOEs is shown in Figure 1.

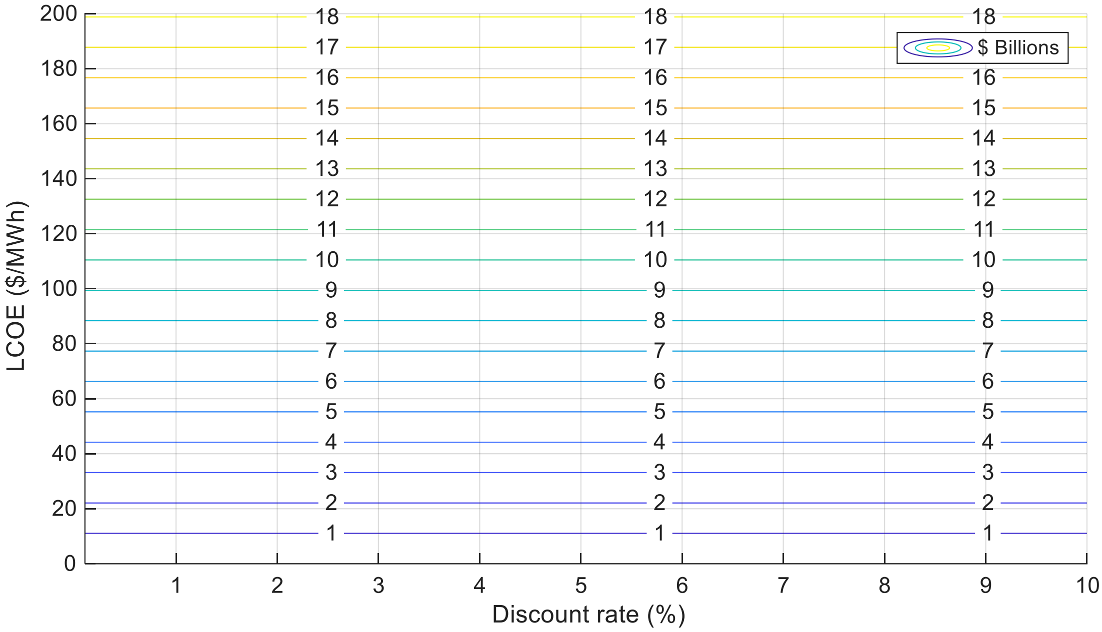

Figure 1 – Total lifetime cost (billions of dollars) as a function of discount rate and LCOE.

The lifetime cost is independent of the discount rate, as per equation (2). The unusual choice of axes is to facilitate comparisons with later plots.

Step 2: Operation and maintenance costs

There is no mature design for a fusion power plant, let alone any operational experience. Nevertheless, we can make a lower bound estimate of the operation and maintenance costs. This is possible by noting that a fusion power plant *is just a thermal power plant* (albeit one with an unusually complex heat source) and then making a reference class forecast.

The U.S. Energy Information Administration publishes historical data on the average annual operation, maintenance, and fuel costs for existing power plants by major fuel or energy source types [19]. Operation and maintenance cost data are plotted in Figure 2 and Figure 3 respectively. Whilst fuel costs are given in the original data, we are excluding them here and optimistically assuming zero fuel cost for fusion.

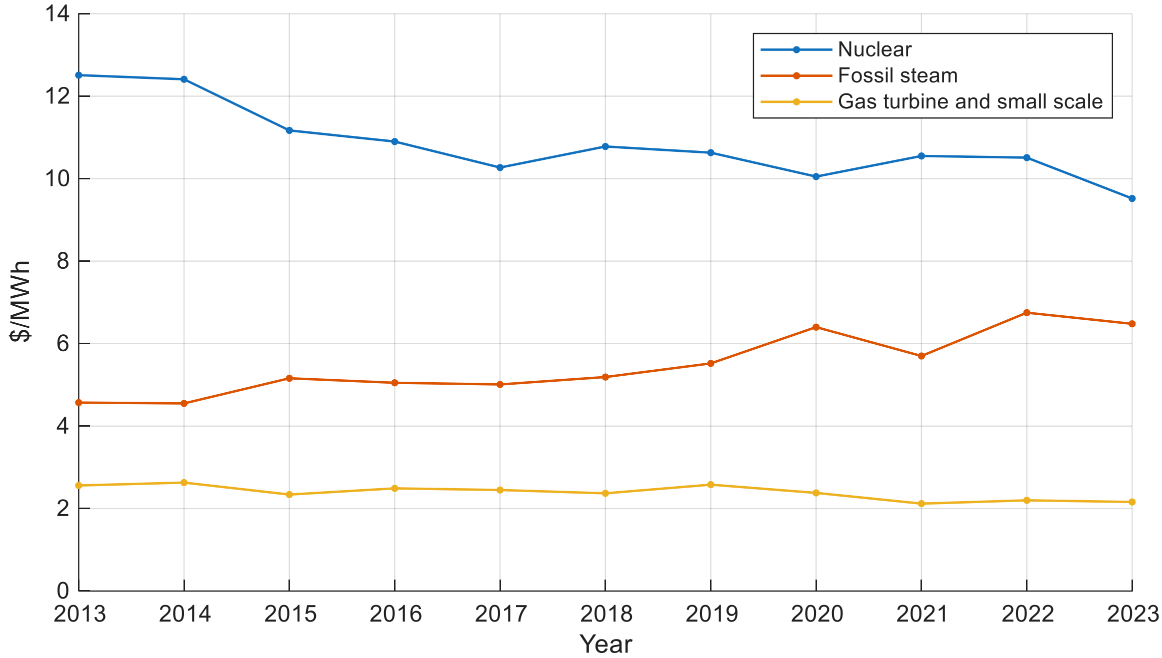

Figure 2 – Average annual operation costs for conventional power plants, [19].

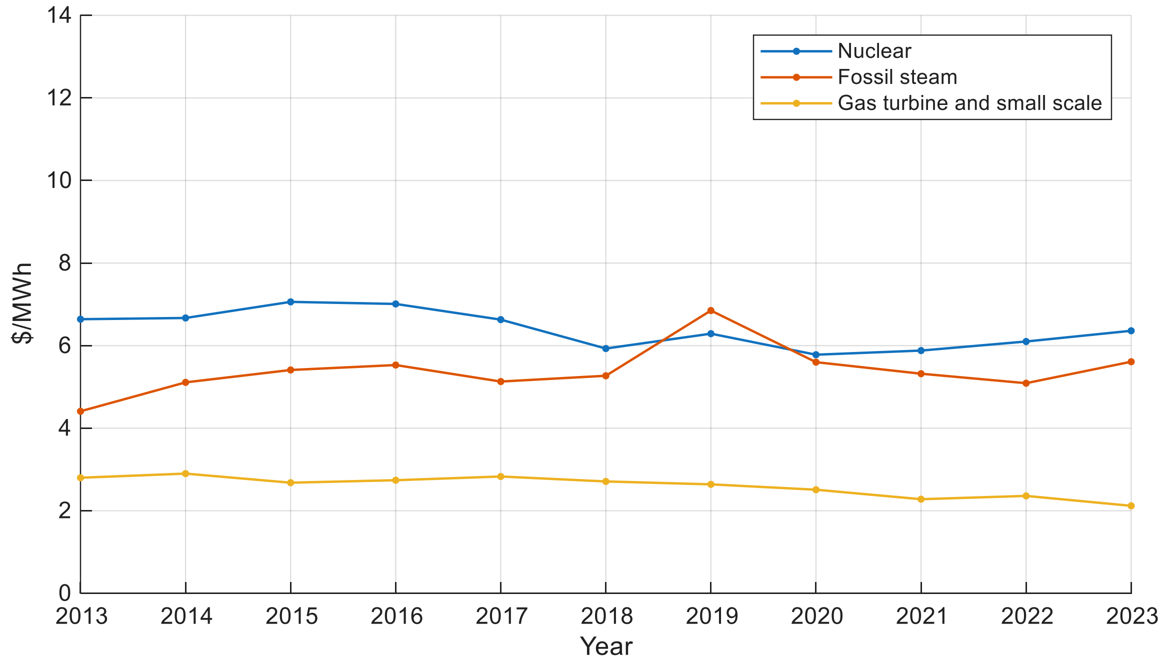

Figure 3 – Average annual maintenance costs for conventional power plants, [19].

Given the additional subsystems and complexity present in a fusion power plant, taking a figure of 8 $/MWh for operation costs and 6 $/MWh for maintenance costs is a reasonable lower bound. Scaling these figures by gross generation gives a projected annual operation and maintenance cost of $76 M.

Step 3: Total capital cost

The total capital costs can be inferred from the lifetime costs as follows:

(1) **Calculate the total levelized annual cost: $113 M.**
This is the total lifetime cost ($4.5 B) divided by the lifetime (40 years). At a minimum, this much income is needed each year to cover the costs over the lifetime of the plant. Note: if electricity can be sold at a higher price, then a profit can be made.

(2) **Calculate the annual expense: $76 M.**
This is comprised of operation, maintenance, and fuel costs.

(3) **Calculate capital cost recovery amount: $37 M.**
This is the amount of money left over each year, after maintenance expenses, to repay the loan: (1) minus (2).

(4) **Assume term of loan: 40 years.**
Setting the term equal to the plant life effectively implies that the power plant is constructed overnight. In practice, the loan duration may be longer than the plant life.

(5) **Assume discount rate: 7 %.**
This is the interest rate paid on the loan. A single value is chosen here without justification simply for the sake of this illustration.

(6) **Calculate capital recovery factor (CRF): 7.5 %.**
This is used to calculate the uniform (in this case annual) payment needed to recover the initial investment cost plus the specified rate of return over the asset's useful life.

This is calculated as a function of (4) and (5) as given by [20]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where i is the interest rate and n is the number of payments.

(7) **Calculate total capital cost: $500 M.**
This is found as the capital cost recovery amount divided by the capital cost recovery factor: (3) divided by (6).

The preceding worked example used the same power plant output, life, capacity factor and LCOE as in Step 1. Repeating the calculation for a range of LCOEs and a range of interest rates yields the results in Figure 4.

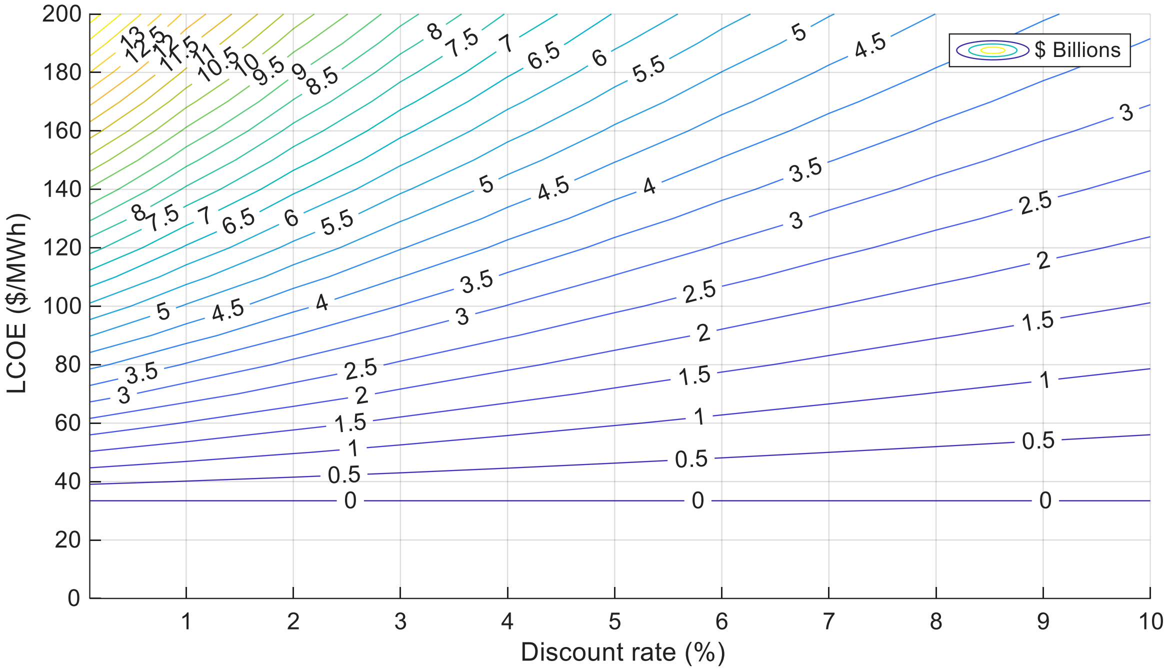

Figure 4 – Total capital cost (billions of dollars) as a function of discount rate and LCOE.

By comparing Figure 4 and Figure 1 the extent to which operation, maintenance, and interest costs dominate capital costs can readily be seen. For example, at 7 % discount rate and LCOE of 50 $/MWh capital costs make up just 11 % of the total lifetime costs.

Step 4: Total direct costs

The total capital cost in Figure 4 includes:

1. Direct costs (equipment, material, and labor to construct the civil/structural, mechanical, and electrical/instrumentation and controls components of the facility).
2. Indirect costs (distributable material and labor costs, cranes, scaffolding, temporary facilities, engineering, construction management, contractor overhead).

3. Engineering, Procurement and Construction (EPC) contracting fees[3].
4. EPC contingency.
5. Owner's costs (project development, studies, permitting, legal, regulatory compliance, project management, engineering, startup, commissioning, land, interconnection, and security).
6. Owner's contingency.

We seek values for items 2-6 so that we can subtract these from the total capital cost and thus infer the direct costs (item 1). Whilst figures will vary slightly from project to project, reliable estimates are readily available – after all what we are costing *is just a power plant construction project*. We can adopt the values reported by the U.S. Energy Information Administration for a power plant with similar gross generation, in this case a 650 MWe net ultra-supercritical coal plant without carbon capture [21]:

2. Indirect costs of 12 % of direct costs.
3. EPC contracting fee of 10 % of the direct and indirect costs.
4. EPC contingency of 10 % of EPC costs.
5. Owner's costs of 7 % of EPC costs.
6. Owner's contingency of 12 % of the owner's costs.

Taken together these figures equate to 48 % of the total capital cost. Therefore, the remaining 52 % of the total capital cost can be attributed to the direct costs, as shown in Figure 5:

[3] Engineering, Procurement and Construction is a type of contract used in the construction industry where a contractor is responsible for the entire project from design to completion. It simplifies project management by allowing the project owner to work with a single contractor for all aspects of the project.

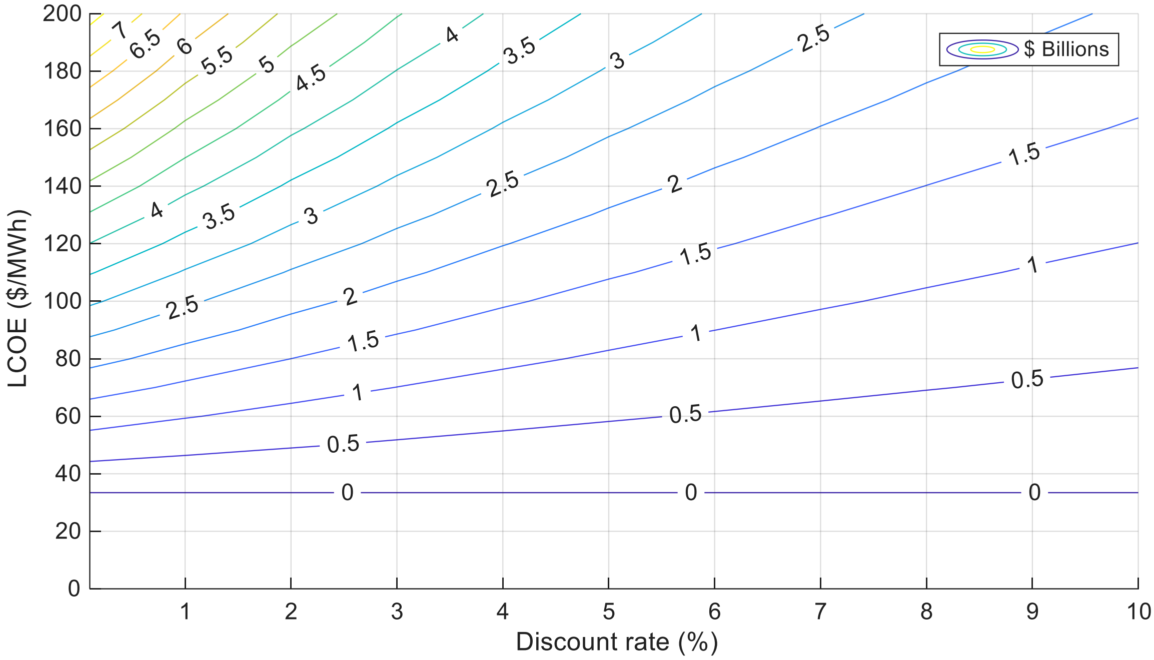

Figure 5 – Direct costs (billions of dollars) as a function of discount rate and LCOE.

Step 5: Fusion hardware costs

The direct costs shown in Figure 5 are comprised of conventional hardware (buildings, steam turbines, water cooling systems, ...) and fusion specific hardware (capacitors, plasma injectors, tritium plant, vacuum systems, ...).

The costs of conventional hardware are readily available. Using information from the U.S. National Energy Technology Laboratory [22] the conventional hardware for a power plant of this size can be found to cost approximately $400 M in 2018 dollars (see Table 2).

	Steam turbine generator	Cooling	Feedwater	Balance of plant	Buildings
Cost	$137 M	$49 M	$43 M	$52 M	$80 M
Efficiency	N/A	40.2%	40.2%	N/A	N/A
MWe gross	688	688	688	688	688
MWe net	N/A	650	650	N/A	N/A
MWth	N/A	1617	1617	N/A	N/A
Heat rejection (MW)	N/A	967	967	N/A	N/A
$/MW	$198,657	$51,067	$44,502	$75,751	$115,878
MW required	726	1226	1226	726	726
Total	$144 M	$63 M	$55 M	$55 M	$84 M

Table 2 – Scaling of conventional hardware costs. 'MW required' is either the gross generation or heat rejection of the fusion power plant as appropriate.

The following items were included:

- Steam turbine generator.
  - Includes condenser, auxiliaries, foundations, piping.
- Cooling costs.
  - Includes cooling towers, circulating water pumps, circulating water system auxiliaries, circulating water piping, make-up water system, component cooling water system, circulating water system foundations. Excludes feedwater system.
- Feedwater system.
  - Includes feedwater system, water makeup and pre-treating, other feedwater subsystems, service water systems.
- Balance of plant.
  - Includes auxiliary transformers, circuit breakers, surge arresters, busbars, fire protection systems, compressed air systems, heating systems, ...
- Buildings.
  - Includes steam turbine building, boiler building, administrative building, circulation water pumphouse, water treatment buildings, machine shop, warehouse, waste treatment building and structures.

Whilst a fusion power plant will not require a boiler building, it will require a specialist building to house the nuclear fusion reactor(s), and a building to house tritium processing plant. Nuclear reactor and tritium processing buildings may be expensive if they rely on special materials and are required to contain tritium during design-basis accidents. Adopting the cost of a conventional boiler building can therefore be considered a lower bound estimate.

Subtracting $400 M from the direct costs in Figure 5, we are left with the fusion hardware costs shown in Figure 6.

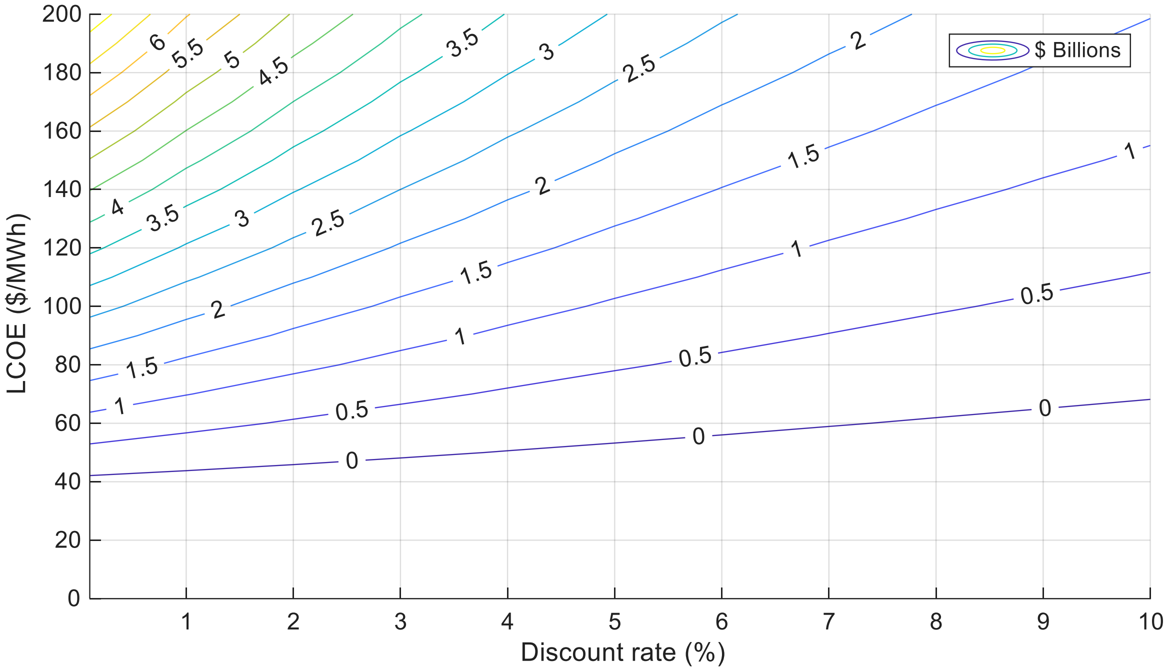

Figure 6 – Fusion specific direct costs (billions of dollars) as a function of discount rate and LCOE.

4. Discussion

The results in Figure 6 show that to achieve an LCOE of 60 $/MWh at a discount rate of 7 % the fusion hardware would have to be produced *for free*. Even at a 2 % discount rate there would only be $500 M available for fusion hardware (e.g., fusion reactors, tritium plant, ...).

Whilst a thorough discussion of discount rates is outside of the scope of this article, some context is necessary to appreciate the results. The International Energy Agency use a range of discount rates in their *Projected Costs of Generating Electricity*: a 3% discount rate corresponding approximately to the “social cost of capital”, a 7% discount rate corresponding approximately to the cost of capital of a large utility in a deregulated or restructured market, and a 10% discount rate corresponding approximately to cost of capital in an environment with relatively higher risks [3]. Nominal discount rates would be higher, reflecting inflation.

It is worth emphasising that the result in Figure 6 has been arrived at despite favourable assumptions. For example, a capacity factor of 85 %. Attaining the assumed capacity factor requires:

- A sufficiently reliable power plant. The power plant would have to be available at least 85 % of the time (i.e., scheduled and unscheduled downtime of less than 18 months per decade). Fusion power plant designs have not yet demonstrated this level of availability.
- Sufficient grid demand. The marginal cost of renewables production is zero. So, when renewable generation is available it is dispatched before higher cost alternatives. In grids with high renewables penetration there are times when the renewables can meet most (even all) of the grid demand. In such circumstances fusion power would not be required, thereby reducing the capacity factor [23].

Shutting down a fusion power plant reduces plant revenue, but does nothing to reduce the capital cost, consequently the LCOE increases. Halving the capacity factor doubles the LCOE.

4.1. Net thermal efficiency

The fusion power plant design considered in the worked example in section 3 cannot achieve an LCOE in the 50-65 $/MWh range at realistic discount rates. Even the higher range of 64-73 $/MWh can only be attained with unfeasibly cheap fusion hardware. This begs the question, why is it that the fusion power plant cannot attain similar LCOEs to conventional power plants despite having free fuel and being assumed to be constructed overnight?

The answer is because of the relatively low net thermal efficiency of the fusion power plant. The net thermal efficiency of the fusion power plant in question is just 17 %, versus 32-55 % for conventional nuclear and coal fired power plants [24].

Net thermal efficiency is important because costs are a function of *gross* output whereas revenue is a function of *net* output:

$$LCOE = \frac{\Sigma\, costs}{\Sigma\, output} = \frac{f(gross\ output)}{f(net\ output)}$$

The costs in the numerator of the LCOE are the costs incurred from generating *all* of the electricity. However, the revenue producing output in the denominator of the LCOE comes only from the fraction of the electricity that is sold (i.e., that portion that the power plant does not consume itself).

In a conventional thermal power plant, the power plant itself does not consume much electricity; the net output is approximately 95 % of the gross output [22].

For the magnetised target fusion power plant considered herein the power plant itself uses the majority – approximately 60 % – of the electricity generated. Only around 40 % of the electricity generated can be sold to the grid. Consequently, for the same net output the fusion power plant needs to generate more than twice the gross output of a conventional power plant. This is illustrated in Figure 7 which shows Sankey diagrams for a conventional thermal power plant (upper) and a fusion power plant (lower) that deliver the same amount of energy to the electrical grid.

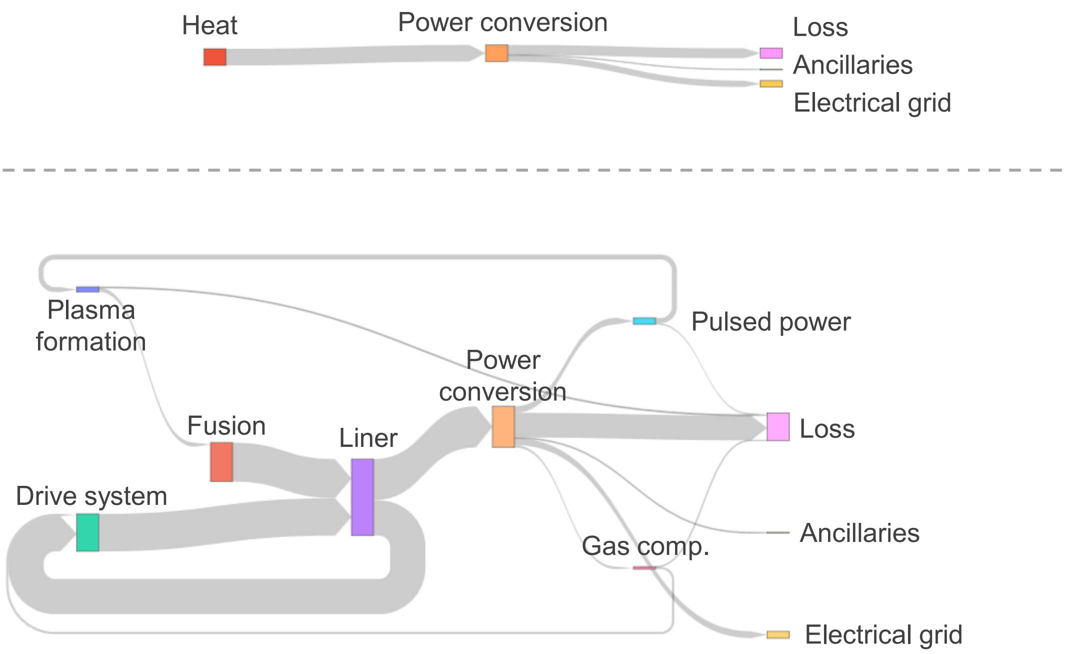

Figure 7 – Sankey diagrams showing the flow of energy in a conventional thermal power plant (upper) and a magnetised target fusion power plant (lower). The amount of energy delivered to the electrical grid is the same in both cases, but the fusion power plant must generate more than twice the amount of gross electricity.

Other fusion power plant concepts also have low net thermal efficiencies. Early tokamak power plants are expected to have plant efficiencies below 20 % [15]. The 2017 DEMO baseline design point had a net thermal efficiency of 24.9 % [7] and a later 'indicative' DEMO fusion power plant design point had a net thermal efficiency of 21 % [25]. As long as fusion power plants are major consumers of electricity, the electricity they produce will necessarily be relatively high cost.

An important corollary of the low net thermal efficiency of fusion power plants is the relatively high thermal loss, as can be seen in Figure 7. Compared with a conventional nuclear fission power plant with a thermal efficiency of 34 %, the fusion power plant in Figure 7 must dissipate twice the amount of heat despite producing the same net electrical output. To first order, on a per megawatt hour basis the fusion power plant would therefore need twice the amount of cooling water as a fission power plant.

4.2. Summary of assumptions

It is helpful to conclude by briefly summarising the assumptions used in this analysis. This allows the analysis to be readily reapplied with less conservative assumptions and/or to other fusion power plant designs.

The analysis presented herein ignores:

- Inflation
- Escalation
- Total cost of construction
- Decommissioning

Accounting for each of these would decrease the funds available for fusion hardware at a given LCOE (or equivalently increase the LCOE for a fixed cost of fusion hardware).

Inflation and escalation manifest in two distinct ways. Firstly, through assumed operation and maintenance costs and conventional hardware costs. The operation and maintenance costs (based on data in Figure 2 and Figure 3) are valid for 2018 (the figure adopted was representative of the period 2013-2023). Conventional hardware costs were consistent with this, given as they were in 2018 dollars. Inflation and escalation would necessarily increase the conventional hardware costs as no adjustments were made for cost increases that have already taken place since 2018. These cost increases would inevitably decrease the funds available for fusion hardware at a given LCOE. Secondly, inflation would occur during construction of the plant. Such cost increases were implicitly neglected by assuming that the power plant is constructed overnight.

Total cost of construction would be substantially higher than the overnight cost. This is due not only to the inflation and escalation, but also because interest must be paid on the capital used for construction. A 10 year construction duration is a reasonable estimate [14]. A fusion power plant that takes 10 years to build with a 7 % interest rate would cost over 70 % more than indicated by the overnight cost of construction [1].

The analysis can be extended to include these effects by adopting values from analogous thermal power plants.

The operation and maintenance costs of a fusion power plant were assumed to be comparable to those of a conventional thermal power plant. In practice the additional complexity and diverse range of additional systems in a fusion power plant would be expected to increase operation and maintenance costs, and by extension decrease the funds available for fusion hardware at a given LCOE.

Indirect costs, EPC contracting fees, EPC contingency, owner's costs and owner's contingency were all assumed equivalent to those of a conventional thermal power plant.

Capacity factor was assumed to be 85 %. This can be seen as overly optimistic, especially for early generations of power plants [5].

Power plant life was assumed to be 40 years. This is optimistic in the short term as fusion is yet to boast a net gain experiment let alone a power plant with a long operational life.

5. Conclusions

By recasting the LCOE forecasting problem it is possible to sense check and, in some cases, invalidate the projected cost of electricity from fusion power plants. The method, which in essence relies on reference class forecasting of major cost contributors, can readily be applied to other fusion schemes where key figures of merit are available or can be inferred: net electrical output, gross electrical output, capacity factor and plant life. In the absence of values for capacity factor and plant life assumptions can be made, or a range of values used.

The worked example considered a hypothetical magnetised target fusion power plant that sells electricity; the economic value of heat was neglected as various barriers make this potential revenue stream difficult to exploit widely. The result showed that under universally optimistic assumptions (in some cases unattainably so) the fusion power plant LCOE was only cost competitive with legacy energy sources when the cost of the fusion hardware was either zero or so low as to be unrealistic.

The relatively high cost of electricity was found to stem from the relatively low net thermal efficiency of the power plant. This serves to re-emphasise a point made elsewhere: for widespread adoption fusion power plants will need net thermal efficiencies that are comparable to existing thermal power plants. This is a necessary, but not sufficient, condition. For example, if operation and maintenance costs are substantially higher (as may reasonably be expected), or capacity factor or plant life are substantially lower than for existing power plants, the cost of electricity from fusion will still be relatively high.

The analysis described herein is not only applicable to magnetised target fusion. It can readily be applied to other fusion schemes that rely on a thermodynamic cycle for generating electricity, such as tokamaks and stellarators. Net thermal efficiency is a key metric for designers of, and investors in, these fusion power plants. As such the net thermal efficiency of fusion power concepts should be reported by designers and the feasibility of claimed efficiencies closely scrutinised by researchers.

A corollary of the low net thermal efficiency was noted, namely that low net thermal efficiency implies large cooling requirements (per unit net electrical energy produced). This limits the number of suitable sites for large fusion thermal power plants.

Declarations

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Competing interests

The author was formerly employed as a Systems Engineer at General Fusion.

6. References

1. M. C. Handley, D. Slesinski, and S. C. Hsu, J Fusion Energ **40**, 18 (2021).
2. J. Emblemsvåg, Energy Research & Social Science **119**, 103897 (2025).
3. International Energy Agency and Nuclear Energy Agency, *Projected Costs of Generating Electricity 2020 – Analysis* (International Energy Agency, 2020).
4. M. Kovari, R. Kemp, H. Lux, P. Knight, J. Morris, and D. J. Ward, Fusion Engineering and Design **89**, 3054 (2014).
5. T. Griffiths, R. Pearson, M. Bluck, and S. Takeda, Prog. Energy **4**, 042008 (2022).
6. S. Entler, J. Horacek, T. Dlouhy, and V. Dostal, Energy **152**, 489 (2018).
7. J. Matthews, A. Pearce, and S. I. Muldrew, Fusion Engineering and Design **217**, 115105 (2025).
8. D. T. Anderson, J. M. Canik, C. C. Hegna, and C. M. Mowry, J. Plasma Phys. **91**, (2025).
9. G. Twinney, Transforming How We Energize the World, The Energy Disruptors: UNITE Summit, Calgary, Canada. https://www.youtube.com/watch?v=bz2guwLq49M&t=712s (2024).
10. E. S. Rubin, N. Berghout, G. Booras, T. Fout, M. Garcia, S. M. Nazir, A. Ramirez Ramirez, S. Roussanaly, and M. Van Der Spek, SSRN Journal (2021).
11. J. Hidalgo-Salaverri, T. Griffiths, Z. Xuereb Conti, P. Cano-Megias, R. Chacartegui, M. Bluck, J. Ayllon-Guerola, A. Mancini, M. Garcia-Munoz, and E. Viezzer, Nucl. Fusion **65**, 036027 (2025).
12. International Atomic Energy Agency, *Opportunities for Cogeneration with Nuclear Energy* (International Atomic Energy Agency, Vienna, 2017).
13. I. T. Chapman and N. R. Walkden, Phil. Trans. R. Soc. A. **379**, 20200019 (2021).
14. B. Lindley, T. Roulstone, G. Locatelli, and M. Rooney, Energy Policy **177**, 113511 (2023).
15. R. A. Mulder, Y. G. Melese, and N. J. Lopes Cardozo, Nucl. Fusion **61**, 046032 (2021).
16. D. Krotez, R. Segas, I. Khalzov, and V. Suponitsky, *Conceptual Design of a Magnetized Target Fusion Power Plant* (2023).
17. General Fusion, An engineering approach to delivering fusion energy - Investor presentation. Securities and Exchange Commission. https://www.sec.gov/Archives/edgar/data/2074850/000110465926005601/tm263812d1_8k.htm (2026).

18. World Nuclear Association, Reactor Database (2025).
19. U.S. Energy Information Administration (EIA), Electric Power Annual (2024).
20. N. A. J. Hastings, in *Physical Asset Management: With an Introduction to the ISO 55000 Series of Standards* (Springer International Publishing, Cham, 2021), pp. 101–122.
21. U.S. Energy Information Administration (EIA), Capital Cost and Performance Characteristics for Utility-Scale Electric Power Generating Technologies (2024).
22. T. Schmitt, S. Leptinsky, M. Turner, A. Zoelle, C. W. White, S. Hughes, S. Homsy, M. Woods, H. Hoffman, T. Shultz, and R. E. James III, *Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity* (National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States), 2022).
23. T. E. G. Nicholas, T. P. Davis, F. Federici, J. Leland, B. S. Patel, C. Vincent, and S. H. Ward, Energy Policy **149**, 112043 (2021).
24. Igor L. Pioro, *Handbook of Generation IV Nuclear Reactors* (Elsevier, 2016).
25. M. Coleman and S. McIntosh, Fusion Engineering and Design **139**, 26 (2019).