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Can Fusion Energy be cost-competitive and commercially viable? An analysis of magnetically confined reactors

Ben Lindley, Tony Roulstone, Giorgio Locatelli, Matt Rooney

Abstract

Driven from investments toward net zero transition global interest in fusion energy is growing. This policy perspective addresses challenges for its commercialization, given the potentially long timeframe to deployment and competing/complementary technologies. We focus on magnetically confined fusion power, specifically tokamaks, as the route to commercialization is clearer and there is some cost data available. For fusion to be competitive beyond 2040, costs will likely need to be at or below ~$80-100/MWh at 2020 price. This will be hard to achieve for early fusion designs both small or large, for which modelling shows energy costs will be greater than $150/MWh even accounting for production learning. This is due to the low power availability from pulsed operation; frequent replacement of vessel components; and low efficiency power cycles. Technology improvements to improve both cycle efficiency and power availability, along with production standardization and long-life components, have the potential to reduce generation costs and enable magnetically confined fusion to be commercially viable. We therefore recommend focusing commercialization efforts on plants with higher thermal efficiency and potential for higher availability as these maximize the probability of fusion energy proving commercially viable. We also recommend that fusion energy be deployed within a proportionate regulatory regime that recognizes its relatively low radiological hazard. Finally, construction of fusion reactors should be planned in fleet/program terms, as commitment to constructing many units will be necessary for it to become commercially viable.

1. Introduction

Globally, interest in fusion energy is growing fed by investors interested in the net zero transition, successful national fusion experiments and the progress towards the completion of ITER. Also, private investment in fusion has accelerated, with 23 private companies declaring ~$2bn funding as of 2021 [1]. Still fusion energy will take several decades to deploy at scale. Also, fusion energy costs are uncertain, and they depend, among other things, upon future technology choices. The objective of this policy perspective is to summarize how fusion energy may fit into the future global electricity landscape; to estimate the cost of fusion energy dependent on the size and nature of the design based on best available data; to compare this cost with that likely required for fusion to be competitive; and hence to identify key policy drivers for fusion energy to become competitive.

Here we focus on magnetically confined fusion power plants, specifically tokamaks both current large designs and the proposed smaller designs, as these have by far the best publicly available cost data. There is a broad spectrum of alternative paths towards fusion power currently under development [2], including various magnetic confinement concepts which diverge to varying degrees. Cost comparison between different fusion concepts is beyond the scope of this paper.

A different way of obtaining the conditions for fusion is inertial confinement in which an imploding shockwave compresses and heats the fuel. The most advanced method, as demonstrated at the $3bn US National Ignition Facility (NIF), uses very high-powered lasers to heat the fuel and create the compressive shockwave. Achieving the symmetrical compression and the high temperature for fusion is difficult. The initial NIF trials up to 2012 failed to show scientific energy gain. Since then, the design of the fuel target, the focusing and phasing of the 192 laser beams have been improved. As a result fusion gain was demonstrated in December 2022, with an output of 3 MJ of energy for 2 MJ of input to the fuel pellet [3]. Whilst this was a groundbreaking demonstration of fusion, there remain significant engineering challenges for inertial fusion. These include better fusion gain, radical improvement in laser efficiency [4] & energy conversion at the target, turning pulse operation every few hours to many times per second, capturing and converting the energy released. Another inertial fusion approach is being developed in the UK by First Light Fusion. It creates the compressive shockwave by means of a high velocity shaped target impacting a fuel pellet [5]. Promising results have been reported using their gas gun arrangement [6]. Because of the early and experimental stage of inertial fusion devices, there is no useful cost information to allow consideration their economic potential. While this may change with new devices, the clearest and best funded route to fusion appears to be magnetic confinement.

1.1. Timeline for Commercialization of Fusion Energy

Development of fusion power requires a transition from R&D to commercial deployment The development and deployment of complex systems such as fusion power plants can be clustered in four main phases.

- **Phase 1 – Demonstration of fundamental technology.** This is the current stage of fusion, with theoretical work and experiments to validate the relevant physics. The ITER reactor is one such demonstration since it will not produce any electricity but will test critical aspects of the design. There are numerous other scientific experiments around the world that simulate fusion conditions, typically at a smaller scale. Very few use both deuterium and tritium required for fusion.
- **Phase 2 – Engineering Demonstrator.** This establishes that the technology fundamentally works and produces electricity sustainably [7]. UKAEA [8] listed essential aspects of an engineering demonstrator to include all systems relevant to a fusion power plant. Such a device does not need to demonstrate industry standards of availability or net efficiency.

- **Phase 3 – Commercial FOAK (First of a Kind).** If an engineering demonstrator is successful, the next step is typically a full-scale system (performance demonstrator) that can then be deployed commercially [8]. This unit is expected to produce electricity that will be sold on the market. This unit will not be economically viable since it will require substantial one-off design and construction costs, may have considerable downtime to address teething troubles and may also need an extended commissioning phase. It might require a range of incentives and subsidies, typical of FOAK technologies, such as governament capital contributions or contract for differences. However, this unit is critical since many investors are reluctant to invest in a commercially untested new technology.
- **Phase 4 – Commercially viable Power Plants** may then be deployed. Such plants might still need some kind of policy incentives (at least in the early years) but would be grounded on proved designs and financed by utilities.

Examples of engineering demonstrators for fusion include STEP in the UK, which is targeted for beginning construction in 2032 [9], and completion around 2040 [10]. Things are similar globally, with various domestic plans to build engineering demonstrators ('DEMO'). Korea, the EU, Japan and China have generally targeted operating such a reactor ~2045-2050, which places commercial deployment in the late 2050s or beyond [11]. Some private sector start-ups propose a more ambitious timeline. Their concepts are based on far smaller reactor, which aim to progress through the 4 phases much faster. For instance the Commonwealth Fusion Systems (CFS) in the U.S. (similarly Tokamak Energy in the UK) target beginning construction of an engineering demonstrator in 2025 [12] and commercialization of their ARC technology in the early 2030s [13]. Fusion power therefore has the potential to make contributions to electricity demand from the 2040s onwards.

1.2. Market for Fusion Energy given Timeline to Widespread Deployment

The need for fusion power must therefore be evaluated according to the energy market when it is to be deployed. The future energy market has been extensively studied, e.g., [14], [15], and is undergoing major changes driven by greenhouse gas emissions reduction targets, falling renewable prices and geopolitical/energy security considerations [16].

Possible markets for fusion include electricity and process heat. Here we focus on electricity as this is the simplest case to address; process heat has a range of different target costs and requirements, including the need to transport heat [17]. However, it is noted that fusion, like fossil fuels, biomass, and fission, produces large amounts of heat and this can be used to meet other energy demand such as district heating, heat for industrial processes or hydrogen production, for which the demand is large. Process heat and cogeneration opportunities for nuclear fusion were recently addressed in Ref. [18]. Given the similarities of the economics and scale of fusion and fission, several recent studies on fission is somewhat relevant for fusion, e.g., Ref. [19].

Global electrical demand is large and as economies grow and as low-carbon electricity replaces fossil fuels, the global demand for electricity will increase even taking into account energy saving from about 27,000 TWh to 40,000 TWh in 2040 [14]. Here we consider scenarios where substantial reductions in fossil-fueled generation, which currently provides 59% of electricity [20], is greatly reduced. This will be necessary if substantial progress is to be made towards net zero targets [15], [21], [22],[23].

Considering the need for decarbonization and/or reduced reliance on fossil fuels, the commercialization of a new technology like fusion energy in the 2040s leaves little time for deployment to make a significant contribution to 2050 emissions reductions targets. Nevertheless, electricity demand is likely to continue to grow beyond 2050 driven by deep de-carbonization and rising standards of those living in developing countries. Markets for fusion energy therefore include (A) new capacity to satisfy a growing demand of electricity, (B) substitution of plants that reached their end of life or are not allowed to operate anymore. Fusion energy therefore has a huge potential market opportunity. Here we focus on utility-scale generation, rather than islanded microgrids or special purpose reactors.

1.3. Target Costs

While future electricity costs and shares are uncertain, and the cost of electricity does and will continue to vary between different countries [24], we consider a potential future scenario in order to derive an estimated target cost for fusion. Example, renewable energy cost figures for 2050 are given in Table 1 (2020 economics). These are subject to uncertainty given the long timeframes involved. Fusion energy will nonetheless need to compete on cost.

Given the low cost of variable renewables, this raises the question: Why pursue fusion energy at all? The primary reason lies in the additional cost required for system reliability that arise as variable renewables reach very high levels of system penetration. High variable renewables shares lead to large weather-driven fluctuations in electricity supply which, when combined with fluctuations in power demand, they cause large swings in electricity supply and hence energy prices. The swings in supply challenges continuity of supply and system reliability. Hence the need of appropriate policies for promoting back-up supplies and energy storage that are at the heart of the additional system costs [25],[26].

From Ref. [27], a system with 50% variable renewables may incur additional system costs of ~$30/MWh, rising to $50/MWh with 75% variable renewables. Such costs are not included in the costs of renewables generation. System costs rise faster as renewable penetration approaches 100%, large amounts of complementary low-carbon supply, energy storage and/or system overcapacity will be required to guarantee that demand can be met [28], [29]. Various academic studies have investigated the feasibility of achieving high renewable shares in different markets. Where they consider long continuous periods of supply and demand, they generally reach similar conclusions that even with highly interconnected power systems, the additional system costs will be large [29], [30]. It is however noted that a recent study [31] used a different modelling method, based on short 'representative' periods for optimization and different cost assumptions yielded lower system costs.

In scenarios with lower variable renewables and therefore lower reductions in carbon emissions is anticipated to be more challenging for fusion electricity, as system costs associated with variable renewables will lower and fusion power may be in competition with unabated fossil fuels, with or without carbon pricing.

An advantage of fusion relative to fission is low radiological source term. This provides the potential to access markets that are unavailable to fission due to political concerns about safety and radioactive waste. This includes countries and/or regions with low public opinion of fission power or political opposition to construction of new fission plants (e.g., Germany, Italy, Japan, Taiwan, many US states [32]). This is contingent upon the policy and public perception landscape during a distinction between fission and fusion, which may not always be the case.

Estimates of the future energy costs of CCS technologies [33], and nuclear fission [34] show they are higher than future variable renewables costs (excluding system costs). Capital costs are shown in Table 2, converted to $ at purchasing power parity. CCS technologies are projected to have higher costs than nuclear fission (and also have various other environmental disadvantages [35] [36].

In Western countries recent nuclear fission projects have experienced large cost overruns and new build LCOEs are currently significantly higher than those for variable renewables[37][33] [38]. However with the right program approach, fission is likely capable of producing electricity at prices low enough to contribute to a system that contains mostly variable renewables [39]. With a substantial program of standard build it would be possible to reduce nuclear fission costs in the West to ~$80-100/MWh [34]. An analysis for the UK [28] suggests that at a nuclear cost of $99/MWh, a mixed nuclear + renewable energy system has the potential to be lower cost that a renewables-only energy system. While this analysis is somewhat UK-specific, it provides a reasonable starting point for viability in other markets. This fission energy cost therefore provides the first target for nuclear fusion to be economically competitive.

2. Methods for Estimating the Cost of Tokamak-based Fusion Energy

We estimate the cost of tokamak fusion energy depending on the number of reactors that are built and the size of these reactors. This is inherently difficult due to the technology being state-of-the-art and the relative paucity of data. There have been a handful of studies (introduced below) that have previously estimated the cost of fusion energy, which mostly rely on some combination of data from ITER; the PROCESS fusion reactor design code originally developed by what is now UKAEA [40]; and, in the US, models produced in 1980s and updated recently in Ref. [41]. We investigate the effect of discount rate, power scaling effects and economy of multiples.

3.1. ***Discount rates***

Here we consider three discount rates:

1. High typical of novel unproven technology 9%
2. Private returns for more mature technology 7%
3. Full or part-Government funded with mature technology 5%

Historically, higher discount rates have been used in cost analysis for novel energy technologies. However, the cost of capital is now much lower, and it appears inconceivable that fusion energy will be deployed in the absence of some form of government support.

2.2. Power scaling effects

There is little public domain economic analysis of the small (~100s MWe) tokomaks that are now being proposed, for example by CFS [42]. We can use scaling models and ideas employed elsewhere to modify the earlier PPCS economic analysis and examine some simple cases as examples.

Here we will consider the cost breakdown of a typical fusion reactor in four categories: magnets, other reactor systems, balance of plant and buildings; and apply scaling factors to each. We use Ref. [43] as the starting point (Table 3), which leads to straightforward power scaling except for the magnets. These constitute a significant component of the fusion reactor's overall cost, and hence warrant special attention. From Ref. [44], the magnet cost scales with the square of the magnetic field and the volume of the magnetically confined plasma, $(B^2V)^{0.6}$.

For the **magnets**, recent designs of fusion reactor now consider high temperature superconductors (REBCO). This is not explicitly considered in Ref. [44] which consider low temperature superconductors as in ITER (Nb_3Sn). Ref. [45] reviews the prospects of lower costs both from the ability to sustain higher power densities and from the economies of production scale. While current REBCO prices were $80-100/kA/m (compared to $6/kA/m for Nb_3Sn) there are plans to reduce REBCO tape costs to $14-23/kA/m. A 2015 ARC design study [42] uses REBCO tape prices in the range $18-36/kA/m. Ultimately, the cost of the magnets is typically dominated by the cost of the structure required to withstand the magnetic field, and hence the cost of the magnets (and the fusion plant) is not particularly sensitive to the cost of the superconductor [42], [44].

For the rest of the fusion reactor itself, we scale based on the fusion power rather than the electrical power, as different fusion reactors have significantly different recirculating power ratios and thermodynamic efficiencies, which significantly affect the electrical power output for a given reactor footprint. Furthermore, recent fusion reactor designs propose higher power densities to reduce costs. Proposed PPCS designs (also ARIES) which provide the economic baseline, have somewhat higher power densities: 1.3-1.9 MW_{Fus}/m^3. ARC and ST150 power density values are double this: 3.2-3.7 MW_{Fus}/m^3 [42], [46]–[49]. We therefore scale according to fusion power using an exponent of 0.5 (~as Table 3) modified by the power density.

For the balance of plant including the power conversion systems we use power scaling according to output power similar to fission and Ref. [50]. For buildings we use power scaling with an exponent: of 0.62 for output power [51] also with an adjustment for the reactor size.

The estimated cost of the reactor is hence:

$$C = C_{ref} \sum f_i S_i$$

Where C_{ref} is the reference cost (determined in Section 3), f_i is the proportion of total cost associated with system i for the reference plant and S_i is the cost scaling factor associated with system i. The relative cost is then the estimated cost divided by the electrical power.

2.3. Production learning rates

Cost reduction through production learning is achieved through the modularization of the design and construction and progressive improvement in production techniques as manufacturing methods are refined. Production learning is a widespread and key strategy of cost reduction in manufacturing. For example, fission energy projects, the use of a standardized design and the regular repetition of build are shown to be very effective in reducing capital costs. Based on energy sector data and similar to previous estimates [52], we use a production learning rate of 10%. This has the effect of a 30% capital cost reduction for the 10th unit. For the small design with its larger numbers (75 units) to provide the same level of power capacity as the larger design the cost reduction is 48%.

3. Fusion Power Plant Data

3.1. Build Schedule Duration

The length of the build schedule affects LCOE by delaying the value of future revenues that are to be discounted. There is very little information about the likely build schedules for fusion power plants.

Ref. [53] reviewed fusion experiment construction time versus reactor radius showing a clear and approximately linear trend between radius and construction time. The largest experiments, ITER and Wendelstein 7-X,* have construction schedule durations of 10-12 years. These are state-of-the-art science experiments, but not include the many additional blanket and power conversion systems required for a power plant. For commercial power plants, repeat construction may be anticipated to reduce build times of subsequent reactors.

There are a few estimates of build timescale for a prototype or FOAK DEMO power plant.

- Ref. [54] gives a build duration of 8 years, followed by 2 years of commissioning for a large 9m radius 5000MW fusion power design.
- Ref. [55] gives a build duration of 8 years also for a 9m, 5000 MW fusion power design.
- Ref. [47] give a construction duration of 10 years for their lower output, but still large 8.4m radius 2000MW fusion power design.

These are estimates for a design that has not been fully developed and have significant uncertainties. Yet, they provide a reasonable indication of the build duration of a commercially oriented FOAK fusion power plant – 8-10 years – and which is similar to that of a large fission power plant. Using the trend of build schedule duration against fusion device size form Ref [53], the smaller 200 MWe ARC plant (with a 3.3 m major radius) might have a build duration in the range 4-5 years and the 100 MWe ST150 (with a 1.5 m major radius) might have a build duration as low as 3-4 years.

3.2. Large (~1 GWe) Power Plant Cost Estimates

In the early 2000s, the European Power Plant Conceptual Study (PPCS) [54] identified four tokamak concepts – A, B, C and D – all sized to produce 1,500 MWe from 2,500–5,000 MW of fusion power (Table 4). These span near-term and longer-term technologies. Near term designs are characterized by less ambitious physics and materials choices but have lower performance in terms of power plant compactness, energy gain and cycle efficiency. European plans for a demonstration fusion power plant, sized for 500 MWe, are currently focused on nearer term technologies [47]. Examples include (but are not limited to) PPCS A and B from the study in Ref. [54]. A key consideration for investors in fusion is whether to move ahead with developing a power plant based on more proven technology, or whether to pursue further R&D with the aim of achieving a fusion power plant with superior performance, which in turn will improve its commercial viability.

From Ref. [54], early tokamak designs are limited to pulsed power, low temperature steam power cycle and uses current materials. It is capable to be deployed as a technology demonstrator immediately following ITER in 2040s, with commercial stations perhaps a decade later. More advanced technology designs such as DEMO2 and some ARIES options could have lower costs. Advanced designs have steady state operation, makes use of improved physics, advanced materials that can stand increased temperatures and large neutron doses and also a higher temperature more efficient power cycle. The most advanced physics, with new and exotic materials might get costs down further but on timescales well beyond 2060. Examples include (but are not limited to) PPCS C and D respectively from Ref. [54].

* It is noted that Wendelstein 7-X is a stellarator, which may have a different trade-off in construction cost and operational performance to a tokamak.

A review of previous cost studies for large fusion power plants gives costs in the range of $4000-$8000/kWe, all at 2020 economics (Table 5). The higher end of the range is for conservative technology with lower costs projected for higher performance technology choices.

Ref. [52] gives capital costs which are all based on the CCFE PROCESS code. They used a 'Wright' production progress rate of 90%, which is based on the number of units produced. This is consistent with the energy industry progress rates from Ref. [56]. FOAK costs (i.e., less one-off design, safety and supply costs) could hence be 35% more than those given above. Ref. [57] provides estimates for a 1 GWe 'DEMO2', with a more ambitious steady state physics and materials package – similar to PPCS (C) but with a low efficiency power conversion cycle.

US ARIES studies are similar in nature to the European PPCS studies, most resembling PPCS(C). They analyze both US and related European design cases, with ARIES capital costs being lower than DEMO equivalents, being $4,000-4,700/kWe for ARIES. Ref. [41] produces capital cost for Euro (C) $6,218/kWe, a little higher than Ref. [52]. ARIES (AT) was defined in the late 1990s and the design parameters where updated in ARIES (ACT) – see Ref. [48]. Capital costs of ARIES AT are also similar $5,616/kWe [48] for 10th of a kind – significantly higher than indicated by Ref. [41].

An econometric study of fusion in the UK energy system for a much larger (3.6 GWe) fusion system [58] used data from Ref. [52], with a single deployment date (2045), but the lower capital cost value is more representative of a PPCS (D) and hence 2070-80 timescales.

Ref. [43] uses a different method based on ITER costs. This study estimated first DEMO costs at $30,000/kWe on the assumption that there is a broad R&D project for DEMO with extensive technology support funded by the project, before the design of a FOAK fusion power system, whose costs are more narrowly focused only including the costs of construction and essential first-off costs: design, safety, supply chain etc. ($12000/kWe). His mature costs are high $9,000/kWe reflecting the low efficiency of the early PPCS (A) fusion power plant design.

The data from Ref. [52] is used as the baseline going forwards, as it has been reported most often and was produced by the author of the PROCESS code which is standard method for EUROfusion studies. Here we select two cases for further study:

- Early physics and materials with a lower efficiency power cycle
- Advanced physics and materials with a higher efficiency power cycle

3.3. Cost Estimates for Small (~100s MWe) Fusion Reactors

Only a few cost estimates are available for FOAK small fusion reactors [59] [42], with capital cost estimates of $29670/kWe and $34500/kWe respectively. Both are ARC-like plants at ~200 MWe using high temperature superconductors.

For completeness, Ref. [60] proposes a very compact 70 MWe design with ambitious assumptions for thermodynamic efficiency and availability (bearing some similarity to PPCS (D) but much smaller), estimating costs at $5600/kWe for first of a kind, although this may be optimistic.

Given the paucity of cost estimates, especially for plants beyond FOAK, the cost of a small fusion reactor will be estimated in the following section based on scaling a reference large plant (e.g., as in Ref. [61]).

3.4. Distribution of Direct Capital Costs

Breakdowns of fusion reactor capital costs from the literature are given in Table 6. Both cases use low temperature superconducting machines.

Going forward we use the Ref. [57] cost distribution aggregated into four categories:

1. Magnet system: 37%
2. Reactor system: 21%
3. Power conversion and balance of plant (BOP): 25%
4. Buildings: 17%

Ref. [42] also provides, cost estimates for ARC excluding balance of plant equipment, with the high temperature superconducting magnets (including steel support structure) compromising some ~80% of the overall capital cost. In general, we see that the largest cost element of tokomak power system are the magnets, with considerable variation in the degree to which this dominates costs.

While technology improvements may change things over the next few decades, it is nonetheless instructive to compare these costs to nuclear fission, which is similarly a high capital cost technology. Typical costs are given in Ref. [62]. For nuclear fission, a much larger proportion of costs are involved in the building and construction (37%) with smaller shares (12-15% each) for the nuclear systems, generating equipment and mechanical support. The main reasons of these differences are for fusion: the very high cost of the super-conducting magnets and for fission: the nature of the containment and other structures which need to be proof against external hazards such as: severe earthquake, aircraft crash and terrorist incidents, while maintaining a leak-tight region around the reactor. Fusion has a much lower amount of radioactive material and does not have the same decay heat problem as fission after shut-down of the reactor. These differences mean the building and safety systems are less complicated and less costly. This view needs to be verified by a detailed safety assessment for a commercial fusion reactor in due course.

Using this breakdown of systems and the rationale of Section 2, cost factors can then be defined.

$$S_{magnets} = \left[\frac{B^2 V_{magnet}}{\left(B^2 V_{magnet}\right)_{ref}}\right]^{0.6}$$

$$S_{BOP} = \left(\frac{P}{P_0}\right)^{0.6}$$

Where P is the net electrical power and P_0 is the reference net electrical power. Note that as the same relative house load is assumed, gross and net electrical power ratios are equivalent.

$$S_{reactor} = \frac{\left({}^{F}/_{F_0}\right)^{0.5}}{{}^{A}/_{A_0}}$$

Where F is the fusion power and F_0 is the reference fusion power. Here, we divide by A, the specific surface area of the plasma to account for power density effects, where $A \propto V_{plasma}^{0.66}$.

$$S_{building} = \frac{\left({}^{F}/_{F_0}\right)^{0.62}}{{}^{A}/_{A_0}}$$

Where again surface area of the plasma is included in scaling as the cost of the buildings is assumed to driven by the cost of the tokamak vessel containment building.

3.5. Operating and Maintenance Costs

Operating and maintenance (O&M) cost estimates are given by Refs. [52] and [41] in Table 7. In fusion reactors, the first wall; blanket; divertor; and plasma heating current drive must be replaced sufficiently frequently that they are typically considered as part of the operating and maintenance (O&M) costs. These account for ~12% of fusion capital costs. These replacement parts costs allow us to take account of two significant effects: (1) lower lifetimes expected of these components for early technology designs, (2) production learning with increased volumes of units.

More compact tokamak designs expose the super-conducting field coils to high levels of radiation. In principle, this could become life-limiting for magnet coils, and they would then need to be replaced at intervals. This issue is addressed by Ref. [42] for their ARC design but it is consider to be capable of being resolved by both shielding the coils and by a small increase in vessel size.

Ref. [57] provides a more detailed breakdown of operating costs, with roughly 38% being O&M and 55% being replacement items, with the balance being fuel, waste and decommissioning. In aggregate, these costs are similar to those of Ref. [52] when fixed and variable costs are considered together.

4. Analysis

In this section, we first develop a framework for calculating the cost of small fusion reactors based on a reference large fusion reactor. Next, we analyze the impact of learning economies. Finally, other factors are considered.

4.1. Cost of Small Fusion Reactors

Given the relative paucity of data for the cost of small fusion reactors, we next calculate their cost based on the scaling laws and cost breakdowns from the previous sections. The ARC machine proposed by CFS is the most developed small fusion reactor concept design and has published the most detailed design data [42]. It is an advanced physics design that is compact resulting from a higher toroidal field derived from high temperature superconductor coils. It has a continuous power operating mode and a high temperature high efficiency power cycle - designed for high efficiency and high availability - therefore the PPCS (C) would provide the closest baseline for the analysis. It has dedicated physics and magnet design programs, but it appears to depend on some long-term R&D for both wall/divertor and blanket materials and for its high temperature power cycle. Because these might not be available in time, it would be useful to consider two ARC cases:

- **ARC-,** based on the ARC design but with long pulse duration operation similar technology to PPCS (A), with a lower efficiency (30%) steam power cycle and current materials that require replacement every two years similar to 'Early' large tokomaks. The size (fusion power) of ARC- is increased to provide the same output power as ARC+ (200MWe).
- **ARC+,** based completely on ARC design with continuous operation and high temperature steam cycle and advanced materials that provide long periods between change-out.

Cost scaling as described in the previous section is performed (Table 8) with an advanced large case from Ref [52] as the economic baseline. Firstly to check this scaling methodology, we predict the cost of an early large reactor from Ref [52] through applying these scaling rules from the advanced large baseline.

The early large design predicted cost is 35% greater than for the advanced large, cf ~40% in Ref [52] giving confidence in the methodology.

The ARC concepts have overall cost multipliers in–the range: 2.11 - 2.31. For comparison, whole plant fission-style cost scaling results in a similar cost multiplier of 2.16. It is notable that the relative contribution of the magnet costs is significantly higher for both early large and ARC-based small reactor estimates than for the baseline: this is driven by lower power density in early large, and higher magnetic field strength to achieve the desired power density in small fusion reactors.

4.2. Impact of Learning Economies

Figure 1 shows the effect that the planned improvements in the technology of large fusion power plants has in reducing capital costs through better power availability and better efficiency. The first standardized commercial unit is called the Next of a Kind (NOAK). It does not have the one-off design, development, and regulatory costs of the FOAK plant. Production learning is important in reducing the effect of the initially very high capital costs. This is particularly the case for small fusion reactors where costs will initially be inevitably higher. Both the higher volumes for the same power capacity and the greater ability to use series factory manufacturing for the smaller components will have the most significant effects. Even so, it appears that the mature small unit capital costs per kWe will be higher than the capital costs per kWe of their larger counterparts.

Capital cost is a key cost driver; therefore, its reduction is broadly reflected at the LCOE level. These graphs show that only through a robust learning process can fusion technologies become competitive with other low-carbon infrastructure such as modern light water reactors. Therefore, investors and policy makers need to approach nuclear fusion not at the project level (i.e., the single reactor unit) but as a program (i.e., the construction of a series of units) [37] [63]. This implies establishing governance at the program level, establishing practices to learn across projects, benchmarking across projects, etc. [64]

Figure 2 summarizes the medium long-term cost for mature fusion power plants. Early large is relatively expensive due to the combination of a relatively high construction cost ($8168/kWe) and a low capacity factor (56%). Considering an improved design – Advanced Large – the construction cost decreases to $5747/kWe and the capacity factor increases to 75%. These two effects improve the fusion economics, decreasing the LCOE into the range $83-135/MWh, overlapping the approximate target cost of $90/MWh. The lower end of this range is consistent with the cost target identified earlier in the paper. As this is the 10th unit and each unit is ~1500 MWe, the cost of building these ten units is roughly $100B (for 15 GWe installed).

Smaller units can compensate for their diseconomies of scale through increased modularization and production learning and from their potentially shorter build schedule (which would reduce financing costs) [65],[66]. Considering the Advanced Small technology option, fusion energy cost of 75 units is in the region of $101-145/MWh – a range that is comparable to 10 units of Advanced Large and also the energy cost of LWR fission reactors. The cost of building these 75 units (also for 15 GWe installed) is roughly $160Bn, hence requiring more funding than Advanced Large program, though with a capital costs ~$1.5 billion per unit rather than ~$10 billion, they could be more suitable for private funding, once proven.

Figure 3 provides a sensitivity analysis using, as a reference case, the 10th unit 'Advanced Large' for a 7% discount rate. The results indicate that capacity factor, discount rate and capital cost are the key cost drivers for the LCOE. This result is unsurprising and similar to what is obtained for other low carbon technologies, such as wind farms or large pressurized water reactors.

- The quantity of electricity produced and hence revenue is proportional to the capacity factor. The majority of the cost are fixed (Fixed O&M) or sunk (Capital cost). The energy cost is almost halved. Consequently, fusion devices need to be designed considering a high capacity factor, i.e., short and infrequent stops of the plant for any planned or unplanned outage.
- The financing discount rate is relevant because these plants are extremely capital intensive, have long construction cost and long operating lifetimes. Consequently, the discussion of their financing (i.e., who is paying for them and at what rate?) should be a key topic of discussion for policy and decision-makers.

Like other low-carbon plants, fusion plants are expensive to build and, hopefully, relatively cheap to operate, making capital cost a key cost driver. The consequence is that construction project and program management have paramount importance.

Topics such as modularization, constructability, rework reduction etc., need to be carefully studied in this setting. Also, technical and manufacturing ways of reducing capital cost more rapidly would have a significant effect. For example, more rapid reduction in the cost of magnets would be important. For a higher production learning rate of 15%, which is typical of such a new technology, for the magnet system, mature capital cost for the small design could be as low as $4865/ kWe and energy cost reduced to $93/MWh (for 7% financing).

4.3. Other Factors Influencing Construction Costs

Tokamak fusion power plants will, like fission power plants, be of relatively unit capital cost, with even relatively small reactors likely be 100s of MWe with a corresponding investment in the $1B range. On the one hand The nuclear systems may be more complex even that fission (due to interaction of plasma, cryogenic systems, magnets, blanket, etc.). On the other hand Due to lower radiological source term, they may not have the same requirement for physical protection and external hazards as fission reactors. It is these requirements and the large and complex concrete structures with the related engineered safety systems that make fission plant progress of construction so lengthy. However, fusion reactors do have a relatively high house load and some components of high capital cost which offset these advantages somewhat, as evident in the above cost estimates.

If fusion systems can be designed largely for factory manufacture rather than site construction, this would avoid the problems that have been observed for fission where poor access for engineers installing components and systems in buildings constrained for space that have already been constructed, impeding construction progress. Similar strategies are now being pursued for fission reactors, and similarly this bias towards factory manufacture and site assembly will benefit fusion costs. It will promote standardization which is key to production learning [63] [67]. Also, there is the potential for much higher labor productivity in factories because of the use of fixed tooling and machines. Also, the better access afforded by factory conditions for component production and system assembly will shorten manufacturing process times. Modular design and build would affect fusion costs, both in reducing capital costs and shortening construction duration [68].

There are many studies of fission energy project showing costs savings as a result of siting more than a single unit on a site. These savings can be from sharing of operating facilities, or from the economic benefits of building units one after another, using shared construction facilities and construction teams. The level of this saving for fission is ~15% . For fusion, it might be larger due the ability to share facilities that are required but not used continuously – such as tritium handling and remote maintenance and waste handling. Here we continue to use the 15% capital cost savings value for multiple units on a site derived from fission.

5. Discussion

Variable renewables are anticipated to dominate future electricity supplies where carbon emissions are either banned or priced or, if geopolitical factors restrict imports. The demand for other low-carbon firm electricity supplies will be real and large. The size of the electricity market for nuclear fusion will depend crucially on its electricity cost and investment risk. It is not a question of whether there is sufficient demand for fusion energy, it is a question of whether fusion is able to produce electricity at a low enough cost (and risk) to be commercially viable.

Because of its sources of fuel are potentially unlimited, nuclear fusion could perform a crucial role in widening access to low-carbon electricity and hence form a key part of the post-2040 electricity generating mix. The timeframe for deployment of fusion means that other sources of low carbon generation will be required over the next 20-30 years. Beyond this period, for it to be deployed widely fusion must compete with other forms of generation on cost.

Forecasting the energy costs of fusion is uncertain both because of its stage of development and the long timescale that are being considered. The analysis performed here considers magnetically confined tokamak reactors as these have by far the most publicly available cost data. Cost estimates for alternative fusion concepts may differ, although depending on the concepts some of the trade-offs may be similar. Nevertheless, for fusion to be competitive beyond 2040 with renewables costs including back-up for reliability, generation costs will need to be at or below $80-100/MWh.

These low energy costs will be hard to achieve for the early technology large fusion designs considered here even with the reduced capital costs from production learning. Modelling shows these energy costs will be greater than $150/MWh. This is due to both the low power availability from pulsed operation and frequent replacement of vessel components, and the low efficiency power cycles of these designs.

The key factors in reducing fusion costs are:

- Reductions in the cost of vessel and magnet systems.
- Longer lifetimes for the replaceable vessel components.
- Improvements in system availability and power conversion efficiency.
- Production standardization, supply and construction cost learning.

Such approaches have the potential for fusion to meet the target generation cost.

More advanced steady-state designs with better materials would take a longer time to develop. They offer the possibility of competitive energy costs based on both repeated production of standard systems and with lower financing costs. Also, smaller (~100s MWe) fusion devices could in principle provide low-cost energy earlier. Their more compact design and larger volumes of production offer the potential for lower costs and faster build times. Also, because of the smaller size of their project funding needs, small fusion power plants may, when proven, be more suited to private financing.

Based on this analysis we provide the following guidelines for policy makers:

- Target higher risk/higher reward advanced technology designs with high power conversion efficiency and the potential for higher plant availability, as these maximize the likelihood that the resultant technology will prove economically competitive. Innovative technologies that can reduce costs, e.g., advanced magnets, are also of high priority.
- Consider fusion plants not on a project/unit level, but as a program/fleet of plants: i.e., promote standardizations in the design, supply chain, governance, financing etc. This will likely require choice of a standardized plant design for each build program.
- Successful deployment of large (~GWe) units is likely to require initial state backing and financing because of their risk and funding requirement, nonetheless these could be economic if implemented consistently. Smaller (~100s MWe) units offer improved prospects for private sector funding, once demonstrated.
- Develop partnerships at international level to enable organizations to share information and maximize synergies across the new fusion supply chains. This also promote international standardisations, that might further reduce construction, operation and decommissioning costs
- Develop a clear and proportionate regulatory environment accounting for the low radiological source term of fusion plants.
- Develop legislative framework at international level, this enables a better standardization of design across countries. This avoids the costly re-design and series of FOAK typical of fissions reactors.

Table 1: Predicted levelized cost of electricity (LCOE) per MWh of Renewables in 2050 [14]

	U.S.	**Western Europe**
Solar	$25	$ 30
Onshore Wind	$30	$ 45
Offshore Wind	$45	$ 30

Table 2. Specific capital and energy costs for selected zero/low carbon energy supply technologies [69]

Technology	Specific Capital Cost	Energy Cost
CCGT with post combustion CCS	$1,377/kWe	$139/MWh
CCGT with pre-combustion CCS	$2,135/kWe	$129/MWh
Oxy-combustion gas (Allam cycle)	$1,966/kWe	$111/MWh
BECCS	$4,377/kWe	$219/MWh
Nuclear Current (Mean)	$6,032/kWe	$136/MWh
Nuclear Future	$5,295/kWe	$99/MWh

Table 3. Power scaling methods in fusion from Ref. [43]***. Exponents Derived in Ref.*** [50] ***from U.S. DOE Data***

Machine Core	**Scaling Factor & Comparison**

Magnets	$E^{0.6}$ where E is the magnet stored-energy [44]. Exponent from historic cost development of superconducting magnets. From Ref. [44] $E \propto B^2V$ where B is magnetic field and V is confined volume.
Vacuum vessel, blanket, divertor system, machine assembly, cryostat, thermal shields, vacuum pumping, fuel systems	$n^{0.53}$ Reactor/boiler plant equipment scaling
Heating & current drive	$n^{0.49}$ Electric plant equipment scaling
Auxiliaries	
Tritium plant, remote handling equipment, cryo-plant & distribution	$n^{0.59}$ Miscellaneous plant equipment scaling
Cooling water systems	$n^{0.53}$ Reactor/boiler plant equipment scaling
Miscellaneous equipment	$n^{0.59}$ Miscaellaneous plant equipment scaling
Buildings and Power Supplies and Distribution	$n^{0.59}$ Structure and improvements scaling

Table 4. European Power Plant Concepts [46]

	A	**B**	**C**	**D**
Major radius in meters (measure for tokamak size)	9.55	8.6	7.5	6.1
Plant efficiency	31–33%	36%	42%	60%
Power conversion cycle	Steam	Steam	Gas	Gas
Technology readiness	Highest	⇨	⇨	Lowest

Table 5. Summary of Fusion Cost Estimates from Previous Studies (2020 prices)

Source	**Technology**	**Rating**	**Unit #**	**Capital Cost ($/kWe)**	**Timescale**
Ref. [52]	PPCS (A)	1500 MWe	10th	$8170	2050
	PPCS (B)	1300 MWe	10th	$7585	2050
	PPCS (C)	1500 MWe	10th	$5750	2050/60
	PPCS (D)	1500 MWe	10th	$4110	2070/2080
Ref. [57]	PPCS (C/D)	1000 MWe	10th	$6068	2050/2060
Ref. [41]	ARIES (RS)	1000 MWe	10th	$4771	2050
	ARIES (AT)	1000 MWe	10th	$4030	2070
	Euro (C)	1500 MWe	10th	$6218	2050/60

Ref. [48]	ARIES (AT)		10th	$5616	
Ref. [58]	PPCS (A)	3600 MWe	10th	$6200	2045
	PPCS (D)	3600 MWe	10th	$3380	Probably 2045
Ref. [43]	PPCS (A)	2000 MWe	10th	$9000	2050

Table 6. Distribution of Direct Capital Costs

	Ref. [70] (500 MWe)	Ref. [57]
Buildings and land	12.8%	17.0%
Reactor vessel/systems	19.7%	15.0%
Magnets	45.9%	37.0%
Vacuum	0.5%	1.0%
Cryo-plant	1.3%	2.0%
Fuel handling	3.6%	5.0%
Heating and current drive	4.4%	6.0%
Cooling	1.9%	4.0%
Control	2.0%	2.0%
Maintenance	3.9%	5.0%
Turbine System	4.0%	6.0%

Table 7. Fusion Reactor O&M Costs (2020 USD)

Source	Technology	Availability	Efficiency	Fixed $/kWe	Variable $/MWh
Ref. [52]	PPCS (A)	0.54	30%	96	19-26
	PPCS (C)	0.75	42%	95	11
Ref. [41]	ARIES (RS)	0.85	40%	121	17
	ARIES (AT)	0.85	51%	121	14
	Euro (C)	0.75	37%	100	18

Table 8. Small Tokomak Cost Scaling Factors & System Cost Shares

Specific Cost Ratios	Baseline cost share	PPCS (A)	ARC-	ARC+	Scaled cost share	ARC-	ARC+
Magnet System	37%	1.61	3.02	2.62	44%	48%	46%

Reactor	21%	1.44	2.05	1.82	22%	19%	18%
Power Conversion & BOP	25%	0.98	2.11	2.11	18%	23%	25%
Buildings	17%	1.23	1.37	1.37	15%	10%	11%
Overall cost scaling		**1.35**	**2.31**	**2.11**			

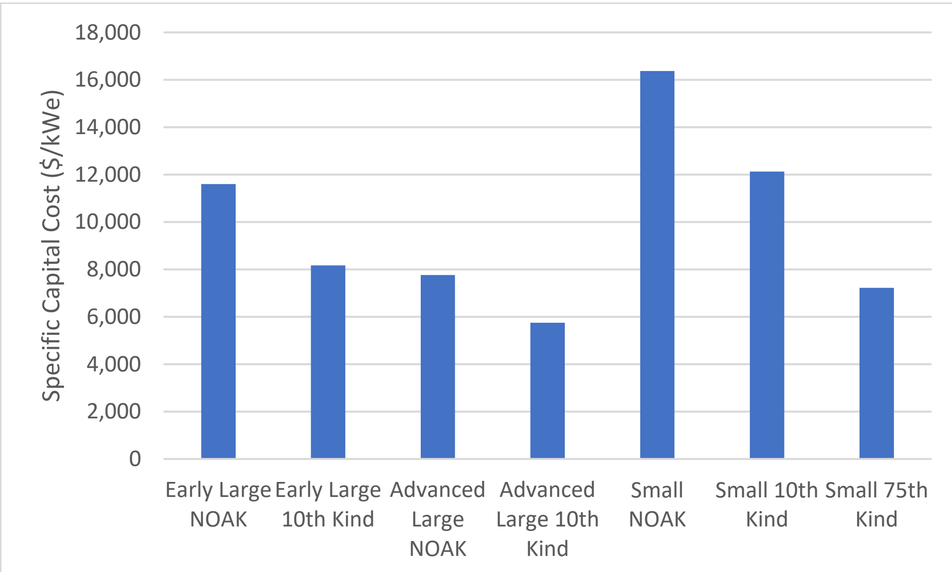

Figure 1. Effect of technology, production learning and size on overnight capital cost

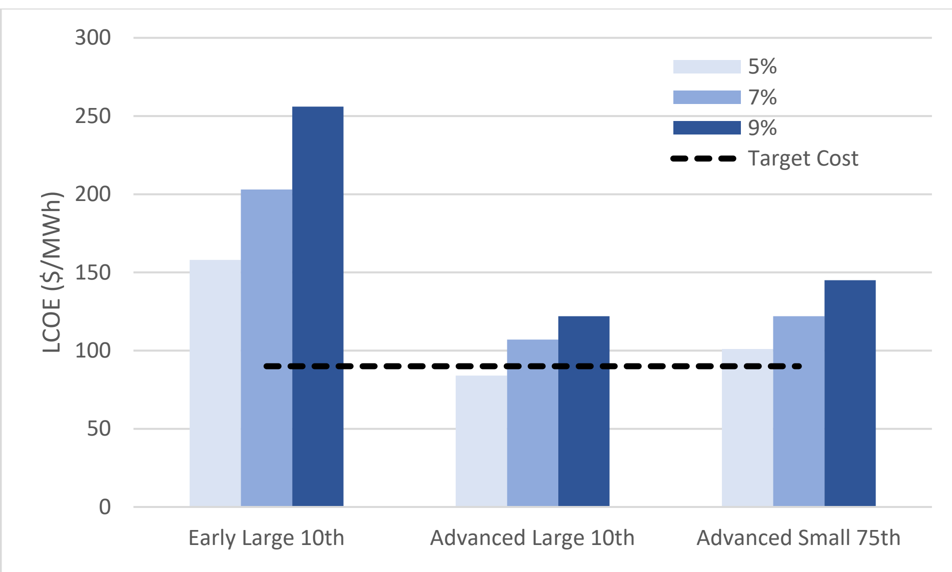

Figure 2. Medium Long term LCOE for fusion power plants for different discount rates

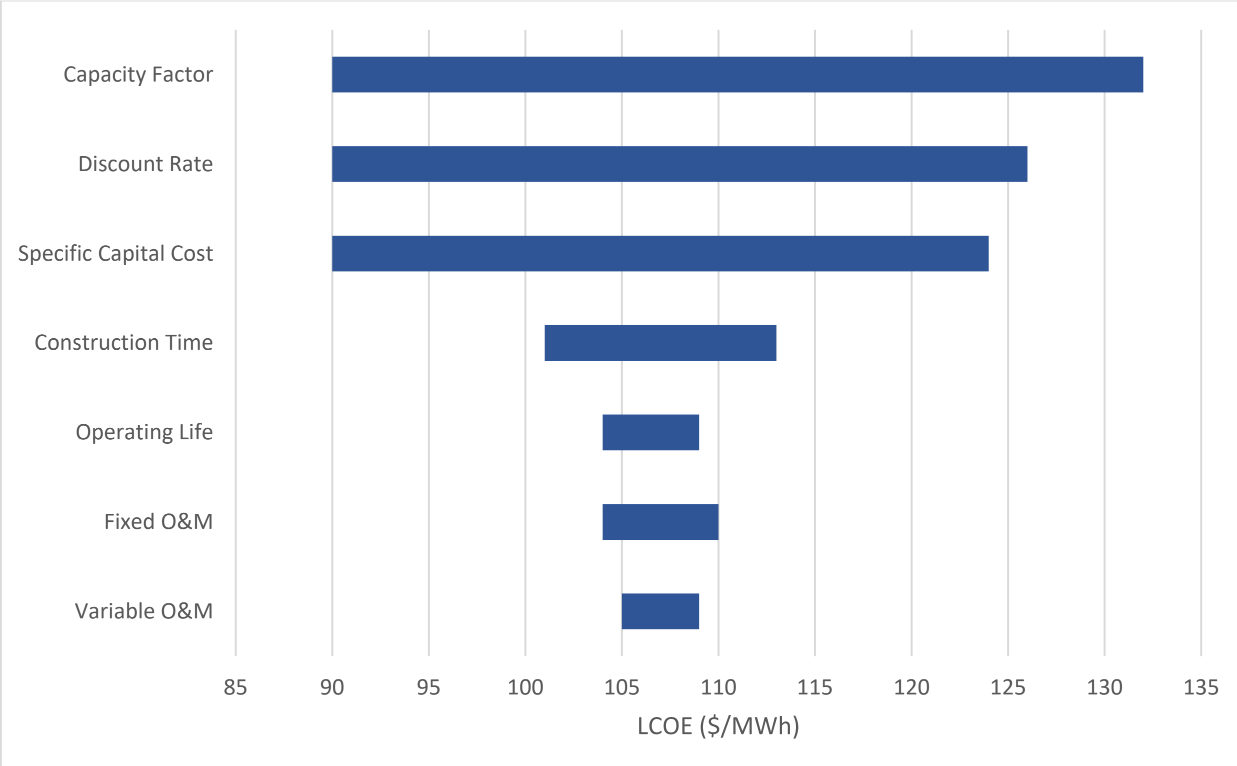

Figure 3. Sensitivity analysis to +/- 20% perturbations in reference value for 10th Advanced Large at 7% Discount Rate

Declaration of Competing Interests

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The IMechE were early investors in Tokamak Energy through their Stephenson Fund and hold a small number of shares in the company. BL is a co-founder of Realta Fusion.

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