Commercialization of Fusion Power Plants

Hanni Lux, Dan Wolff, and Jack Foster

***Abstract*— With the ITER project entering the second half of the construction phase and various national and international plans for fusion prototype power plants being in early to advanced stages, fusion has entered the delivery era. With the urgency of the climate crisis being at the forefront of government policy agendas, it is important to focus on the commercialization of fusion power plants to support decarbonization commitments. This work argues that the cost optimization of fusion as well as the development of a compelling value proposition enhances the contribution that fusion can bring to target energy markets. In particular, it focuses on how both aspects are being considered for the Spherical Tokamak for Energy Production (STEP) program (Wilson *et al.,* 2020) which is currently developing both the conceptual design for a prototype power plant as well as a pathway to commercialization on its mission to "Deliver a U.K. prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion."**

***Index Terms*— Commercialization costs, fusion power generation, fusion reactors, tokamaks.**

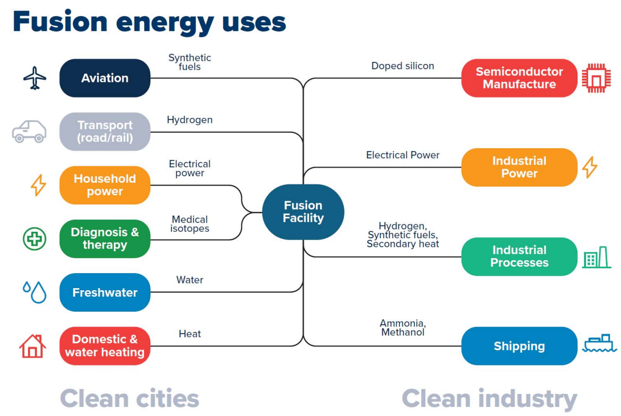

Fig. 1. Overview of different potential use cases for fusion energy, which should be considered on the path to fusion commercialization.

I. Introduction

The 26th UN Climate Change Conference of the Parties in November 2021 in Glasgow has again highlighted the importance of action against climate change for our planet. Fusion was for the first time represented at this summit, which is reflecting the position fusion that is starting to take as a part of the global mix of solutions in addressing climate change. Investments into private fusion as well as the creation of private fusion companies have risen strongly in recent years [19], further reflecting the interest in fusion as a commercially available energy source.

The ITER project, the currently biggest international fusion project, is entering the second half of its construction phase (see Bigot this conference), while multiple national and international endeavors are on their way to design the next step on the way to commercializing fusion.

This work focuses on two aspects relevant to the commercialization of fusion: 1) the commercial pathway and 2) a cost optimized power plant design. Each aspect will be addressed in turn in Sections II and III. We summarize our results in Section IV.

II. Commercial Pathway

To maximize the value proposition that commercial fusion can offer, a range of potential applications are being considered either in addition to or in place of baseload electricity for commercial power plants following the Spherical Tokamak for Energy Production (STEP) prototype power plant. While the STEP prototype power plant is explicitly targeted at delivering at least 100 MWe to the U.K. national grid [9], opportunities to progress technologies related to other applications are also being explored. Techno-economic analysis was carried out for a commercial fusion facility considering several possible outputs along with a variety of associated technology options [14]. Table I shows an example output of the techno-economic analysis, in this case for direct electricity conversion from charged particles (direct electricity conversion has been deselected from further consideration).

This analysis indicated that there are a variety of viable alternative applications/outputs which a commercial fusion facility could deliver, thereby maximizing the overall market penetration of commercial fusion, and Fig. 1 shows a range of potential uses for commercial fusion energy that have been considered in our analysis and deemed worthy of further consideration, grouped into those which could meet the needs of a city and an industrial cluster on the left and right, respectively.

The outputs shown in Fig. 1 can also be considered in terms of their primary energy input from the fusion facility. Neutrons and charged particles can be used directly to produce medical isotopes and dope silicon. The heat produced can be exported as an output in its own right or used to produce electricity. The remainder of other outputs (hydrogen, synthetic fuels, ammonia, methanol, and water) all relies on varying combinations of heat and electricity [14].

Fusion is a predictable low carbon technology with an ability to provide neutrons, a variety of grades of heat and electricity. This places it in an excellent position to make

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TABLE I
EXAMPLE TECHNO-ECONOMIC ANALYSIS OUTPUT FOR DIRECT ELECTRICITY CONVERSION FROM CHARGED PARTICLES (NOTE: DIRECT ELECTRICITY CONVERSION HAS BEEN DESELECTED FROM FURTHER CONSIDERATION)

Readiness level for the state-of-the-art implementation of the technology	Sub-system validation in a laboratory environment (TRL 4)
Readiness of the technology for use with a fusion reactor	Concept design developed with analytical substantiation
R&D Degree of Difficulty	• Very high degree of difficulty. • New capability development operating on different physical principles to existing capabilities. • Probability of success: 50%
Principal outputs	Electricity to grid
Output value in addition to the baseline (fusion reactor with traditional thermal-to-electric conversion)	49 Mwe increase (+4%) compared to thermal to electric conversion alone
Efficiency	Charged particle to electricity: 55 to 65%
Capital cost in addition to the baseline (fusion reactor with traditional thermal-to-electric conversion)	£214m+
Operational cost in addition to the baseline (fusion reactor with traditional thermal-to-electric conversion)	£21.4m per year
Revenue from sales	£31m per year
Payback	22 years
Footprint / siting / environmental	8,500 m2 (all needs to be at low vacuum) Large increase in tritium containment volume / tritiated materials

a significant contribution to achieving and sustaining global decarbonization commitments. It therefore offers the opportunity to displace multiple currently carbon-based energy sources outside of electricity such as, e.g., industrial heat in a way that renewables would find hard.

Fusion-driven production of hydrogen and synthetic fuels has enormous potential to decarbonize many of the more challenging areas to address in the quest for net zero carbon emissions, such as aviation and heavy industry. Provided that the appropriate palette of materials can be developed for the operating environment, which is a challenging endeavor, the anticipated temperature outputs of 600 °C and above, available from a commercial fusion plant, are well suited to high efficiency production of hydrogen and synthetic fuels via high-temperature electrolysis or thermochemical routes [14].

There are a range of approaches being considered to rethink and reimagine the way in which energy carriers are produced. Much of the thinking regarding reducing project cost, schedule, and risk for nuclear fission plants [7] is equally relevant to the development of commercial fusion plants.

There is a tension between the need to have a consistent repeatable design that can be cost optimized and the requirement to meet the needs of a variety of customers in different markets and geographical regions. This can be addressed to an extent by harmonization of regulatory regimes. Furthermore, combinations of outputs could be provided by fusion energy hubs based on a common core architecture but tailored to the specific needs at each location [14].

With the current and anticipated growth of renewable electricity generating technology [15], consideration needs to be given to the optimum role for commercial fusion to play within this evolving energy landscape. The exact deployment model will vary depending on the context, with a more traditional baseload electricity generating plant in some markets. Flexibility in the mix of outputs delivered by a fusion energy hub can complement zero marginal cost renewable electricity while allowing continuous operation of the fusion island [14].

To realize any of these long-term ambitions for fusion to significantly penetrate the energy market, we need to get over the critical investment phase:

"Development [of a new energy technology] needs an 'investment' phase to build up industrial capacity, […], During [which] the cost is dominated by the capital investment, which allows for a simple comparison of different energy technologies." [2].

III. COST OPTIMIZATION

Fusion power plants are complex, highly technical, large-scale infrastructure endeavors that have never been built before. As a result, any prototype fusion power plant can be expected to cost a substantial amount. To both optimize value for money of any fusion prototype plant program as well as to assure the extrapolation of the prototype to a commercially viable power plant, both the capital and operational costs of the prototype need to be optimized.

The costs of fusion power plants are determined by a range of different factors and therefore need to be optimized on all fronts.

A. Global Levers to Cost Optimization

There are several factors that impact the cost of a fusion power plant that are independent of the specific fusion technology or detailed design choices.

The regulatory regime of a power plant has a significant impact on the cost of all components, subsystems, and their operation. As fusion has very different safety requirements from fission, it is essential that fusion power plants are regulated proportionately rather than blindly adopting a regulatory regime that has been designed for technology with inherently different risks. Fusion, therefore, needs a risk appropriate regulatory regime [17]. Due to the inherently different safety risks for fusion power plants, the regulatory regime does not need to be as restrictive to allow comparable levels of public safety to fission, allowing a larger focus on asset protection. This allows risk-tolerant investors more freedom to invest.

Furthermore, there is an opportunity for fusion to establish and internationally harmonized regulatory regime that allows for a globally competitive supply chain. Early efforts toward this goal are being coordinated by International Atomic Energy Authority (IAEA) [5].

Another lever that assures a pathway to commercially competitive fusion power plant is a commitment to building a fleet of them nationally or internationally, if an internationally harmonized regulatory regime exists. Such a commitment together with a design optimized for modular, factory-based construction can enable critical cost reductions through learning by doing from first of a kind to *n*th of a kind and, hence, result in overcoming the barriers in the critical investment phase required to successfully establish fusion as a competitor in the wider energy market [2], [3].

For commercial power plants, the financing and interest rates of loans have a general impact on the total capital cost of a commercial power plant. The regulated asset-based financing model currently considered for fission in U.K. might give an advantage to funding of future commercial fusion power plants and its application should be investigated, if fusion is not remaining a fully state-funded endeavor [10], [18].

B. STEP Costing Methodology

A detailed cost analysis of the STEP prototype power plant has been carried out. As both the STEP design and its cost estimate are confidential and cannot be shared publicly, their results are only reported in documents internal to the STEP program. This work aims to share important results from that analysis with the wider fusion community to support the cost optimization in the wider fusion community. In the following, we report the high-level summary of the STEP costing methodology as is feasible within the page limitations of this conference proceeding and with the confidential constraints of the STEP program.

The STEP cost analysis uses predominantly the fusion standard cost breakdown structure from the STARFIRE report [11] with amendments relevant to more modern fusion power plants as, e.g., including costs of a divertor or bespoke to the STEP design, which cannot be reported here. It furthermore adapts parts of the published fission Generation IV (GEN IV) cost breakdown structure [16], where it is relevant to report costs in a more granular way aligned with more modern ways of reporting costs for power plants as, e.g., for the site development costs and the indirect costs.

All costs in the model are being reported in 2017$ and historical data has been inflated in $ using various relevant U.S. inflation indices specific to the technology, e.g., from https://data.bls.gov/cgi-bin/srgate for switchgear.

To estimate the different cost components with that structure a mixture of top-down and bottom-up cost approaches are being used where the earlier is estimating costs by comparison to similar items in other projects that are then scaled to the right values and the latter is adding up the specific cost items as, e.g., materials and manufacturing costs individually to get the total system/subsystem cost. Data sources for these estimates range from both internal to external to fusion; publicly available to confidential; as well as historical to modern data, where applicable location specific data has been chosen to be U.K. specific and outside of London. It is the aim of the STEP program to develop this to a fully bottom-up cost model in £specific to the STEP site location with modern cost data from the STEP-specific supply chain.

This cost estimate is then combined with information about the STEP design inside the PROCESS systems code [12], [13] to estimate the total costs and analyzed regarding the highest cost components and the factors with the biggest impact on costs in the design.

Due to the different stages of design maturity, the different stages of an existing, partially existing or a nonexisting supply chain for the different fusion power plant components, as well as limited resources in updating the model, some parts of the estimate have higher certainty than others. However, due to the early stage of the STEP design, all estimates are more reliable as differential than absolute cost estimates. "Early-stage cost estimates are unreliable predictors of the eventual cost of mega-projects. This is valid across all nuclear technologies and also large nonnuclear mega-projects" [8].

C. Design Specific Levers to Cost Optimization

The biggest influence on power plant lifecycle costs can be achieved during the early design phase, where a broad design space can be explored for relatively low costs through shallow and simplified investigations (see Killingbeck's presentation at SOFE 2021). Design changes in during construction on the other hand come with large financial penalties and should be avoided [8].

Costs need to be addressed holistically considering all parts of the product lifecycle to avoid optimizing capital costs at the expense of, e.g., operational/maintenance costs. Furthermore, it is essential to address cost optimization in a framework appropriate to the stage of the design. Overinterpreting early cost models can be as detrimental as not optimizing for costs in the early design phases.

It is essential to design for manufacture and involve construction companies early in the design to achieve the desired cost [8].

Detailed cost analysis for the STEP program confirms that tokamak fusion power plant costs are dominated by buildings and bespoke reactor components that to first-order scale with the size of the reactor. The large expenses on building costs are shared with fission, e.g., [8] and fusion should therefore assure that all advances in modular construction techniques investigated by the fission industry are applied to construction on fusion.

Modularization not only needs to be considered for buildings. Large reactor components that cannot be shipped to site such as, e.g., the ITER PF coils not only increase the cost of manufacturing the components, reduce opportunities for cost reduction through learning by doing, but their manufacturing facilities take up more space on the reactor site as well as creating the need for more expensive on-site buildings.

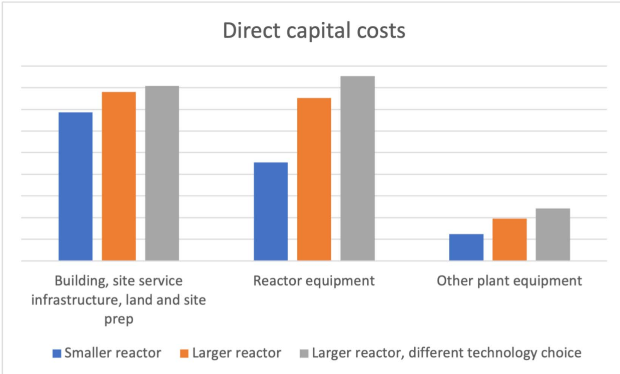

Fig. 2. Comparison of changes in direct capital costs between different sized reactors and reactors with different technology choices aiming for the same net electric output.

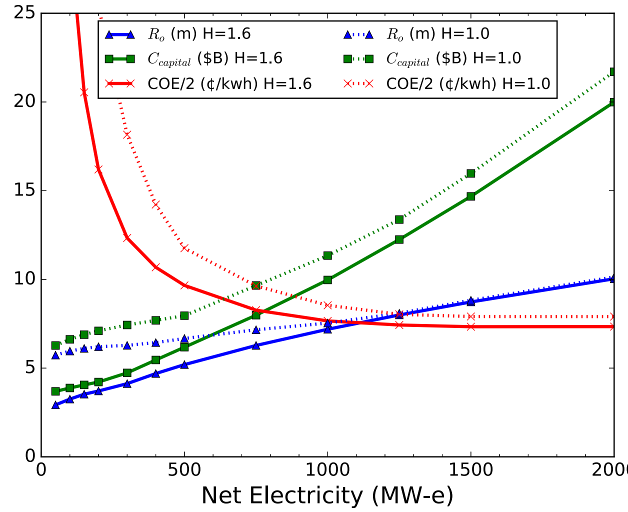

Fig. 3. "Variation of estimated capital cost (green), major radius (blue), and estimated cost of electricity (red) with assumed net electric output power for a compact tokamak pilot with [two variations of] H_{98y2}." Figure and caption reproduced from [4] with kind permission from Wade and Leuer.

In the STEP design, the reactor size is a bigger cost driver on overnight construction costs and therefore capital expenditure than possible technology/material choices or reductions that can be achieved by value engineering. Therefore, the size is optimized within the set of requirements and sufficient margins to allow for resilience of the naturally limited analysis in the early conceptual design phase.

This is shown in Fig. 2, where we compare three different reactor costs. The building, site service infrastructure, and site services costs change mildly due to the different gross electric power between the different designs that drive changes in the cost of the turbine hall. The reactor equipment shows stronger changes with size than with technology choices, when aiming for the same net electric output.

On the STEP program, following the determination of an appropriate size, to optimize the value at a fixed size and therefore cost, key system efficiencies need to be optimized and recirculating power reduced. Appropriate technology choices and value engineering will be used to impact cost on the next level.

Fig. 3 gives an indication of the order of magnitude of the electric output of the smallest, commercially viable magnetic confinement fusion power plant. The specific numbers are expected to vary with the assumptions on the power plant design, but the general trend that: 1) higher net electric machines are expected to lead to higher capital costs and 2) the cost of electricity is not competitive for small machines, where the high parasitic power loads required are larger than the net electric output produced is expected to hold. Similar results have been previously seen by Sheffield *et al.* [6, Fig. 21(a)] for a generic magnetic confinement fusion reactor and the trends of the curve for cost of electricity suggest that there is a sweet spot for the size of the smallest, commercially viable magnetic fusion reactor, which seems to be in the region of 500–800 MW in this analysis but could easily be at higher or lower net electric output values depending on the specific design considered. Commercial successors of the STEP prototype design are therefore expected to sit in the equivalent region relevant to the extrapolation of the STEP design.

IV. Conclusion

In this work, we have investigated the commercialization of fusion power plants from two perspectives: 1) determining the optimal value proposition of fusion in regard to the energy market sector to target and 2) the cost optimization of fusion power plants to assure that they are commercially competitive. This work raised many generally applicable aspects of these two areas but focusses on the application of the results to the U.K. STEP program, which investigates STEP and their pathway to commercialization.

It summarizes the results of a techno-economic analysis of different potential use cases for fusion energy and discusses the tension between a single cost-optimized repeatable design and the need to flexibly adjust the energy source to different markets and local demands.

The work then discusses the different levers on costs that need to be addressed on a variety of levels to assure that fusion will end up being competitive and will be able to successfully penetrate the energy market. These cover global aspects, such as the regulatory regime, commitment to a fleet of reactors of the same type, and financing models. On the design-specific side, the role of buildings and reactor sizes as cost drivers is discussed, followed by optimization of efficiencies and other technology choices.

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To obtain further information on the data and models underlying this article, please contact PublicationsManager@ukaea.uk.

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