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Commercialisation of Fusion Power Plants*

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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 commercialisation of fusion power plants to support decarbonisation commitments. This work argues that the cost optimisation 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 STEP (Spherical Tokamak for Energy Production) [13] prototype reactor to assure the STEP programme succeeds in its mission to "Deliver a UK prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion."

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 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 has risen strongly in recent years [3], 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 B. Bigot this conference) while multiple national and international endeavours are on their way to design the next step on the way to commercialising fusion.

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

II. Commercial Pathway

To maximize the value proposition that commercial fusion can offer, a range of potential applications can be considered either in addition to or in place of baseload electricity. Techno-economic analysis was carried out for a commercial fusion facility considering several possible outputs. 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.

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 a significant contribution to achieving and sustaining global decarbonization commitments.

In particular, the anticipated temperature outputs available from a commercial fusion plant are well suited to high efficiency production of hydrogen and synthetic fuels. Fusion driven production of hydrogen and synthetic fuels have 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.

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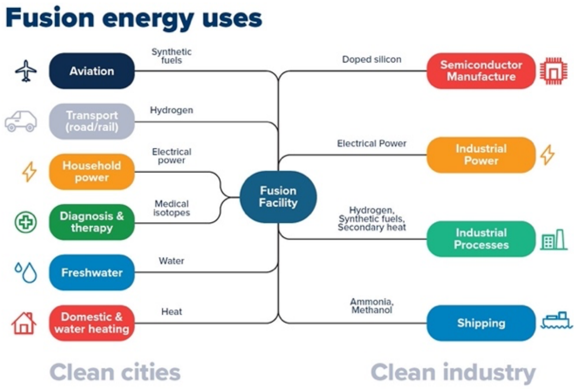

Figure 1. Overview of different potential use cases for fusion energy which should be considered on the path to fusion commercialization.

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 [9] are equally relevant to the development of commercial fusion plants.

There is a tension between the need to have a consistent repeatable design which 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.

With the current and anticipated growth of renewable electricity generating technology 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 whilst allowing continuous operation of the fusion island.

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.” [4]

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 programme 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 a technology with inherently different risks. Fusion, therefore, needs a risk appropriate regulatory regime [1].
Furthermore, there is an opportunity for fusion to establish an internationally harmonised regulatory regime that allows for a globally competitive supply chain. Early efforts towards this goal are being coordinated by IAEA [7].

Another lever that assures a pathway to commercially competitive fusion power plant is a commitment to building a fleet of them may that be nationally or internationally, if an internationally harmonised regulatory regime exists. Such a commitment together with a design optimised for modular, factory based construction can enable critical cost reductions through learning by doing from first of a kind to nth 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 [4,5].

For commercial power plants, the financing and interest rates of loans, have a general impact on the total capital cost of a commerical power plant. The regulated asset based financing model currently considered for fission in the UK, 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 endeavour [11,12].

B. 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 S. Killingbeck's presentation at SOFE 2021). Design changes during construction on the other hand come with large financial penalties and should be avoided [10].

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 [10].

Detailed cost analysis for the STEP Programme 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. [10] and fusion should therefore assure all advances in modular construction techniques investigated by the fission industry are applied to construction on fusion.

In the STEP design, the reactor size is a bigger cost driver 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.

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.

Figure 2 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 a) higher net electric machines are expected to lead to higher capital costs and b) 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, are expected to hold. Similar results have been previously seen by Sheffield et al. [8] in Figure 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.

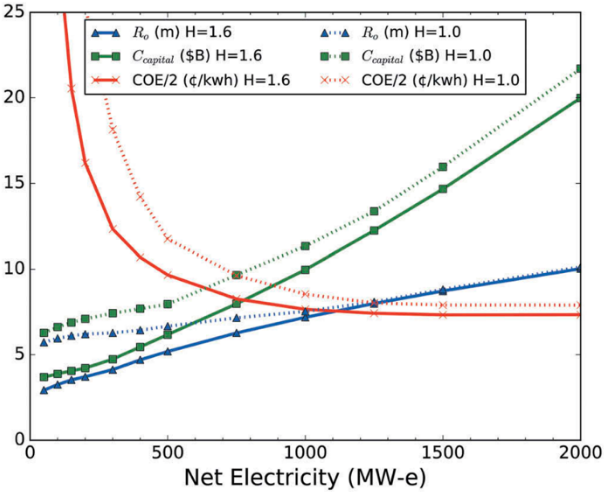

Figure 2. "Variation of estimated capital cost (green), major radius (blue), and estimated cost of electricity (red) with assumed net electric output power for a compact tokamak pilot with [two variations of] H_{98y2}." Figure and caption reproduced from [6] with kind permission from M. Wade.

IV. SUMMARY

In this work, we have investigated the commercialization of fusion power plants from two perspectives: 1) Determining the optimal value proposition of fusion in regards of the energy market sector to target as well as 2) the cost optimization of fusion power plants to assure 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 UK STEP programme, which investigates spherical tokamaks for energy production.

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 fusion will end up being competitive and will be able to successfully penetrate the energy market. These cover global aspects like 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 are discussed, followed by optimization of efficiencies and other technology choices.

V. REFERENCES

[1] "Gov.uk," October 2021. [Online]. Available: https://www.gov.uk/government/news/uk-set-to-be-first-country-to-legislate-for-safe-and-efficient-rollout-of-fusion-energy.

[2] M. Rooney, T. Roustone, G. Locatelli and B. Lindley, "Fusion Energy: A Global Effort - A UK Opportunity," IMechE, Assystem, 2021.

[3] M. Windridge, A. Holland and T. Bestwick, "The global fusion industry in 2021," Fusion Industry Association and the UK Atomic Energy Authority, 2021.

[4] N. J. Lopes Cardozo, A. G. G. Lange and G. J. Kramer, "Fusion: Expensive and Taking Forever?," *J Fusion Energ,* vol. 35, pp. 94-101, 2016.

[5] M. Middleton and P. Guest, "Nuclear for net zero," Energy Systems Catapult Limited, Birmingham, 2020.

[6] M. R. Wade and J. A. Leuer, "Cost Drivers for a Tokamak-Based Compact Pilot Plant," *Fusion Science and Technology,* vol. 77, no. 2, pp. 119-143, 2021.

[7] C. Willis and J. Liou, "www.ieaea.org," 2021. [Online]. Available: https://www.iaea.org/fusion-energy/safety-in-fusion. [Accessed 07 January 2022].

[8] J. Sheffield, R. A. Dory, S. M. Cohn, J. G. Delene, L. Parsly, D. E. T. F. Ashby and W. T. Reiersen, "Cost Assessmenbt of a Generic Magnetic Fusion Reactor," *Fusion Technology,* vol. 9, no. 2, pp. 199-249, 1986.

[9] E. Ingersoll, K. Gogan and J. Aborn, "Rethinking Deployment Scenarios for Advanced Reactors," EPRI, 2021.

[10] J. Buongiorno, M. Corradini, J. Parsons and D. Petti, "The Future of Nuclear Energy in a Carbon-Constrained World," MIT, 2018.

[11] "gov.uk," 26 October 2021. [Online]. Available: https://www.gov.uk/government/news/future-funding-for-nuclear-plants.

[12] S. A. Morse, "Hinkley Point C," National Audit Office, 2017.

[13] H. Wilson, I. T. Chapman and C. Waldon, "One small STEP...," *Nuclear Future,* pp. 46-49, 2020.