Extrapolating Costs to Commercial Fusion Power Plants

Jack Foster*†, Hanni Lux*, Samuel Knight*, Dan Wolff*, Stuart I. Muldrew*

United Kingdom Atomic Energy Authority

Culham Science Centre

Abingdon

Oxfordshire

OX14 3DB, UK

†jack.foster@ukaea.uk

Abstract—**For mega-projects like fusion power plants, modularity is a key enabler to cost and schedule efficiency e.g. [1]. One way of achieving more modularity is aiming for higher numbers of smaller fusion reactors. Previous work [2], [3] has demonstrated that the Levelised Cost of Electricity (LCOE) of commercial magnetic confinement fusion power plants falls at a decreasing rate with increasing net electric power. Furthermore, net electric power increases more rapidly than size/cost. This is because as fusion power increases the proportion of energy being exported as net electric power plateaus but the size of plant required increases linearly. Increases in plant size increase upfront capital costs and project complexity. Therefore there is an optimal design point beyond which any increases in net electric power continue to increase the project cost and complexity but deliver only marginal gains in LCOE. This helps identify a sweet-spot between better economy of size and economy of scale.**

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

I. INTRODUCTION

Many different prototypes or demonstrator fusion power plant concepts are in their conceptual or even engineering design phases [4]–[9]. Estimates of costs of prototype/demonstrator fusion power plants and their potential commercial successors have been attempted in order to understand the potential commercial viability of specific concepts to support investment decisions into specific designs [10]–[13].

However, estimating costs of prototype or demonstration fusion power plants is difficult due to the often still preliminary designs combined with a non-existing supply chain for many bespoke technologies or materials. Extrapolating to commercial fusion power plants without a clear design is even harder and uncertainties are large. As a result, forecasts of commercial viability of fusion are often built on many assumptions that cannot be validated or refuted until the next set of prototype plants has been built. However, it is crucial to understand which factors impact the costs of commercial power plants to address the right validations either on prototypes or separate rigs/facilities on the path to commercialisation. Relative costs can be used to determine expected cost drivers for commercial power plants and help determine decisions that affect the balance between operational and capital costs.

The Spherical Tokamak for Energy Production (STEP) programme is consciously designed to test the smallest scale of prototype fusion power plants by targeting at least 100 MW of net electric output [14]. This assures the prototype is at lowest capital costs to demonstrate electricity production and fuel self-sufficiency, but is not expected to produce electricity at commercially competitive costs. While we expect commercial power plants to have higher net electric output to have commercially viable costs, this work is exploring more the expected impact on major radius and net electric output for potentially smallest commercially viable scales.

In Section II, we describe our methodology used in this work. In Section III, we analyse our results, and in Section IV, we draw some conclusions and assess potential next steps.

II. METHODOLOGY

A. PROCESS

PROCESS [15]–[18] is a systems code for assessing the engineering and economic viability of potential fusion power plant designs using simple 0D and 1D models of the reactor and all plant subsystems. It uses a constrained optimisation solver to find an optimal solution given a user-specified Figure-of-Merit (FoM, e.g. minised major radius) while simultaneously adhering to user-selected engineering constraints and physical laws (e.g. a fixed net electric output). PROCESS does this by varying iteration variables within user-defined bounds in order to satisfy both the FoM and the constraints. The simplicity of the models within PROCESS allow for rapid iterations of power plant designs while also providing an integrated overview of the plant as a whole. The results can then be used to inform more detailed and specialised design work but needs to be interpreted within the limitations of the simple models that cannot capture all real life aspects.

B. Cost Modelling in PROCESS

Due to their highly integrated nature, estimating costs for fusion power plants is ideally done in the same tool as the integrated plant design is created, to allow trade offs and evaluations of all design drivers including costs to be taken into account. Subsytems and facilities could be costed independently and then totalled to give a whole plant cost but this would not capture any interdependencies between systems. For example, if the superconducting magnets and cryoplant

were costed independently, it could be overlooked how their size affects the pumping power required for the cooling, which then has a knock-on effect on the recirculating power and net electric output of the plant.

These oversights can be avoided by using a systems code like PROCESS where not only are the physics and engineering models fully integrated, but the cost models are too. The ability for rapid iterations mentioned above also lends itself to costing fusion power plants, allowing for continuous evaluation and reevaluation of estimates for subsystems, and the plant as a whole. The built-in ability to scan in a desired variable also facilitates extrapolating a particular design and its costs up to a commercial scale plant, an example of which we will discuss in detail in the next section. However, due to the simplicity of the cost evaluation, especially in the extrapolation towards commercial plants, these cost models are more relevant for differential cost assessments than absolute cost assessments.

C. Scans

To extrapolate to a commercial scale plant, we started with a plant design with a Spherical Tokamak (ST) reactor similar to the current conceptual design point of the STEP Prototype reactor [19]. We then performed a scan in net electric output $P_{net,elec}$: 100MW - 2GW, in steps of 25MW, minimising major radius [1]. Some of the important parameters are listed in Table I. The major radius at the start point, and the parameters which are fixed, are consistent with the current STEP Prototype Powerplant design point [19]. The additional parameters listed have been allowed to vary as part of this study, and therefore do not correspond to any baseline design.

Once the scan was successfully performed, a plot of which can be seen in Fig. 1, the point at 1.2GW was selected, around which we performed some sensitivity analysis on certain parameters to explore their impact on LCOE:

- **Allowable blanket fluence** (MW-yr/m^2) - Determines lifetime of blanket/first wall based on neutron wall load
- **Allowable divertor fluence** (MW-yr/m^2) - Determines lifetime of divertor based on divertor heat load
  - Neither of these fluences are currently consistently influencing the plant availability and therefore only impact operational costs. This is not an issue in regimes where the overall plant availability is consistent with those lifetimes but this is unlikely over the entire scan range
- **Nth-of-a-kind (NOAK) factor** - represents the cost of an item/system at its Nth generation with respect to its 1st generation (due to e.g. improved manufacturing, mass production etc.)
- **Thermal efficiency** - efficiency converting total thermal power into gross electrical power. It was shown in [2] how critically the thermal to electric conversion efficiency impacts the estimated capital costs. As capital costs are expected to dominate the LCOE for commercial fusion

power plants, this is expected to have a similarly significant impact on LCOE
- **Availability fraction** - what percent of the time the plant is producing electricity. Given that achievable availability fractions on commercial fusion power plants cannot be understood without building demonstration/prototype fusion power plants, scanning this parameter helps us understand the impact of different availability factors on LCOE
- **Heating and Current Drive (HCD) efficiency** - wall-plug efficiency of HCD systems. As the HCD systems are expected to be the source of highest recirculating power in a tokamak, having higher efficiency systems is being explored as an option to reduce LCOE by increasing net electric output
- **H-factor (IPB98(y,2))** - radiation corrected H-factor [20], [21]. Varying the H-factor helps us explore the effect of uncertainty in the plasma performance in the design and potential performance gains if higher performing plasma scenarios can be found
- **Gyrotron redundancy** - ratio of gyrotrons needed for start-up to flat-top. PROCESS sets the flat-top heating and current drive requirements in line with what is needed to achieve the relevant plasma current. This is also to allow system redundancy. Depending on the design a higher amount of HCD will be needed for start-up/ramp-down or for redundancy to cover unreliable systems. Reducing the ratio between the the flat-top HCD requirements and the overall gyrotrons costed, assumes that going towards commercialisation we can create more reliable HCD sources and learn to ramp-up plasmas more efficiently

The point for the sensitivity study was chosen as it has an achievable net electric output with respect to the starting point design, also there are diminishing returns in LCOE reduction beyond this point.

In the next section, we will discuss the results of these scans in more detail, as well as any potential implications for current and future endeavours to design fusion power plants.

III. RESULTS

The scan in net electric output is plotted in Fig. 1 where the blue line is LCOE normalised with respect to the value at 100MW net electric and the red line is major radius. Firstly, it demonstrates a potentially obvious but still worthwhile point: that by building a bigger device, the power plant is not only generating more electricity, but is doing so in a more cost efficient way, reducing the LCOE. However, it is the size of this reduction that is most striking, reaching as low as ~20% of the LCOE of a 100MW device. It is worth noting that the major radius only begins to increase at a net electric output of ~500MW, at which point the LCOE has reduced to ~30% of that of a 100MW device. Nevertheless, STEP's target of 100MW is to account for margins and uncertainties. Secondly, as mentioned previously, there are dimishing returns in LCOE reduction beyond ~1.2GW. This behaviour is driven predominantly by the large recirculating power to net electric

TABLE I
SUMMARY OF KEY SCAN PARAMETERS

Parameter	Start Point	Analysis Point	Scan Range	Input/Output
Major radius, R (m)	3.6	4.9	N/A[a]	Output
Aspect ratio, $A = R/a$	1.8	1.8	Fixed	Input
Elongation, κ	2.99	2.99	Fixed	Input
Triangularity, δ	0.54	0.54	Fixed	Input
Toroidal field at R, B_T (T)	3.2	3.2	Fixed	Input
Net electric, $P_{\text{net,elec}}$ (MW)	100	1200	100-2000	Output
Fusion power, P_{fus} (MW)	1460	5800	N/A	Output
HCD power, P_{HCD} (MW)	109	304	N/A	Output
H-factor[b], $H_{\text{IPB98(y,2)}}$	1.5	1.12	0.93-1.12	Input
Thermal efficiency (%)	37.5	37.5	35-60	Input
Gryotron redundancy (%)	100	100	10-100	Input
Availability fraction (%)	75	75	70-85	Input
Allowable divertor fluence (MW-yr/m^2)	25.0	25.0	5.0-60.0	Input
Allowable blanket fluence (MW-yr/m^2)	20.0	20.0	5.0-60.0	Input

[a]This was an iteration variable for all PROCESS runs, with a range of 3.6-7.5m.

[b]This was an iteration variable for the PROCESS runs (except the H factor scan) with a range of 0.8-1.6.

A table of a some parameters relevant for the plots and scans discussed in this work. "Start Point" refers to the 100MW starting point of the net electric scan, "Analysis Point" refers to the 1.2GW point where the sensitivity analysis was performed, and "Scan Range" refers to the range over which a scan was performed in a respective parameter.
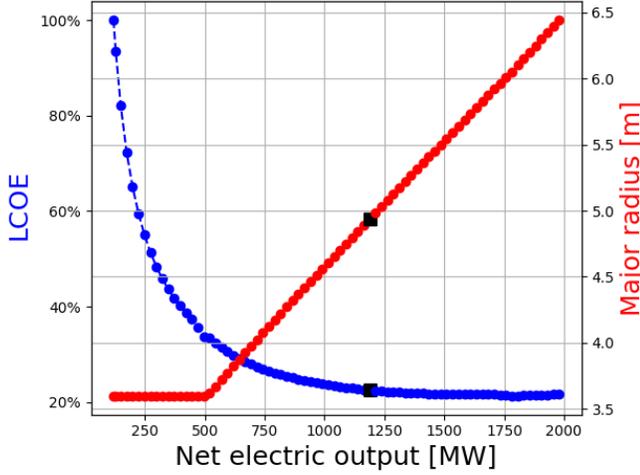

Fig. 1. Plot of scan in net electric output, with LCOE (blue) and major radius (red). The black square corresponds to the point used in the sensitivity analysis.
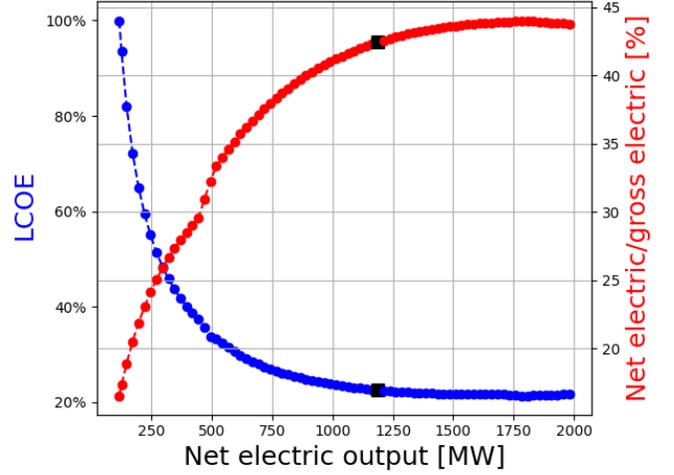

Fig. 2. Plot of scan in net electric output, with LCOE normalised to the value of the 100MW net electric starting point (blue), and gross electric output (red). The black square corresponds to the point used in the sensitivity analysis. The break around 500MW is likely due to the change in major radius.

output ratio at low net electric output. This can be seen in Fig. 2 where, for example, 100MW net electric is only ~17% of the gross electric whereas 1.2GW net electric is ~42% of the gross electric. At 2GW net electric, this output is ~44% of the gross electric, meaning that for only 2% more efficient net-gross electric ratio, substantially more power needs to be generated in a larger device, driving up the capital cost and complexity of the plant for very little reduction in LCOE. The initial flatness of the red line in Fig. 1 is due to the initial design being able to generate more electricity in a machine of the same size. Despite minimising major radius, PROCESS cannot make the machine smaller as it is limited by the imposed engineering constraints on the inboard build. A similar plot is presented in [2] for a conventional aspect ratio device.

The sensitivity analysis is presented as a tornado plot in Fig.

3. Here the LCOE scale should be thought of as a "zoomed in" section of the LCOE axis in Fig. 1 and Fig. 2. This plot illustrates the impact of different parameters on LCOE with the black line representing the initial design point (the black square in Fig. 1 and Fig. 2). We will discuss some interesting features of these results:

- **Allowable divertor fluence** - this clearly has a large effect on LCOE, but it's worth noting that the greatest impact happens over a short range of values, 5.0-25.0, beyond which little is to be gained. A similar behaviour is observed for the allowable blanket fluence although with a smaller impact. This is due to the respective component having a lower lifetime at lower allowable fluence, resulting in more frequent replacements, increasing operational
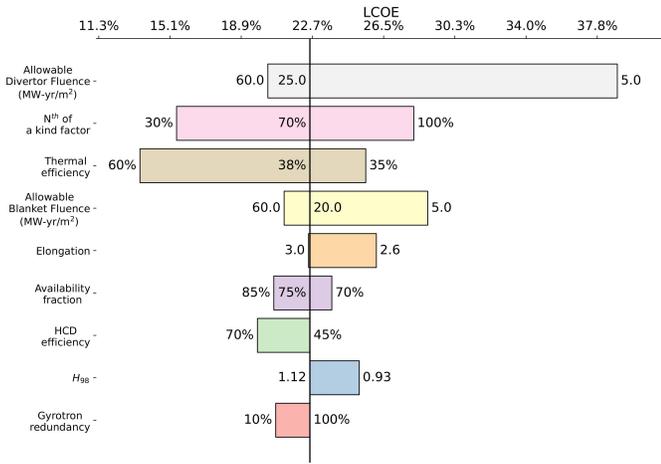
Fig. 3. Tornado plot of sensitivity analysis around 1.2GW point in scan (black line). See Section II-C for scan parameter definitions.

Fig. 4. Plot of major radius vs. net electric output for different max allowed values of P_{sep}/R.

expenses and hence LCOE.

- **NOAK** - unsurprisingly, there is a linear relationship between NOAK and LCOE, due to the fact that this factor is a purely multiplicative one. This factor represents the effects of economies of scale such as the establishment of suitable supply chains, R&D programmes into manufacturing, waste, and maintenance, all of which will be empowered by a fleet approach to future fusion power plants.

- **Thermal-to-Electric conversion efficiency** - here we see another expected trend where a greater thermal-to-electric conversion efficiency results in more net electric for the same thermal power, decreasing LCOE. What's interesting here is that for just 3% improvement in efficiency (from 35% to 38%) we get ∼3% reduction in LCOE, which, while not a large improvement, does suggest that gains can be made in reducing LCOE without having to improve thermal-to-electric efficiency all the way up to 60%. Such a high efficiency would be a result of, for example, higher temperatures from in-vessel components (IVCs) or higher coolant temperatures. Both of these would require either more robust materials for the IVCs, coolant pipes, and heat exchangers, or more frequent replacement of these components, driving up cost.

In Fig. 4, we plot major radius against net electric output for different maximum allowable values for P_{sep}/R, where P_{sep} is the power across the separatrix. These values are chosen as a result of the example for DEMO where $P_{\mathrm{sep}}/R = 20\mathrm{MW/m}$ corresponds to a divertor heat load of ∼ $10\mathrm{MW/m^2}$ [22]. The maximum of this parameter acts as a proxy for the upper limit of the allowable heat load on the divertors, effectively corresponding to the resilience of the divertors. As the scans were run with the machine in double-null mode, P_{sep}/R max should be halved for the max allowable heat load for each divertor, assuming perfect double-null control. We see that the range of
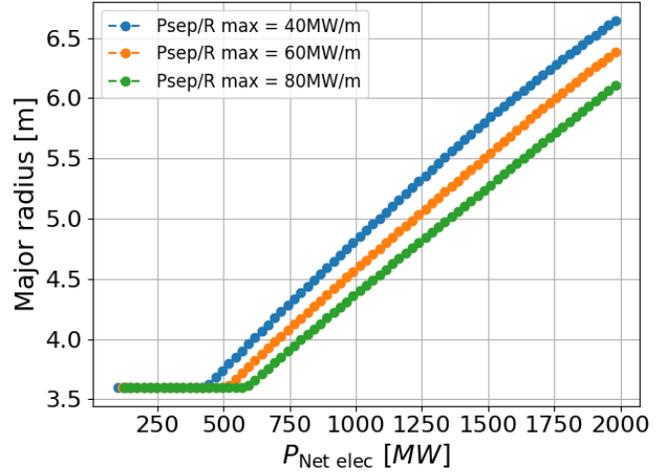
net electric outputs achievable in a 3.6m device increases with P_{sep}/R max. This makes sense as when designing a device, P_{sep}/R can be kept below its limit either by decreasing P_{sep}, e.g. by increasing the core radiation fraction, or by increasing the radius, or, more likely, a combination of the two. Therefore once P_{sep} can no longer be reduced for a given R, the machine has to increase in size in order to keep P_{sep}/R at/below its limit. Hence while the inboard build is the constraining factor for STs at small R, eventually the divertor begins to constrain the design, as has been observed with conventional aspect ratio devices [22].

IV. CONCLUSIONS

In this work, we have analysed the extrapolation of costs of an ST fusion power plant up to commercial scale. While this work has focused on a STEP-like power plant, many of the trends identified are generally applicable.

It summarizes the results of a two-stage analysis: 1) a scan in net electric output to evaluate the effect on LCOE when moving to commercial-scale output, and 2) a sensitivity study on a selection of parameters and their effect on LCOE for a commercial-scale plant. It is apparent that significant reductions can be made in the LCOE of fusion power plants when moving from prototype to commercial power plants. The greatest reduction is made by building higher output plants where beyond around 500MW this necessitates physically larger machines. However, a point is reached beyond which there are dimishing returns, as evidenced in Fig. 1. This is a result of the change in reciruclating power when moving from low to high net electric output, as seen in Fig. 2. Further reductions can be made through various systems, with the degree of impact on LCOE being documented in Fig. 3.

The work then discusses the constraining factors in an ST, highlighting how while the inboard build constrains the design at small major radius, eventually the heat load on the

divertor becomes the constraining factor, forcing the machine to increase in size.

Acknowledgment

References

[1] B. Flyvbjerg, "Make megaprojects more modular," *Harvard Business Review*, vol. 2021, pp. 58–63, 11 2021.

[2] 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. [Online]. Available: https://doi.org/10.1080/15361055.2020.1858670

[3] J. Sheffield, R. A. Dory, S. M. Cohn, J. G. Delene, L. Parsly, D. E. T. F. Ashby, and W. T. Reiersen, "Cost assessment of a generic magnetic fusion reactor," *Fusion Technology*, vol. 9, no. 2, pp. 199–249, 1986. [Online]. Available: https://doi.org/10.13182/FST9-2-199

[4] G. Federici, "Status and prospects for fusion development in europe," *Selected Papers from the 30th IEEE Symposium on Fusion Engineering*, 2023, presented at SOFE 2023, see proceeding.

[5] Y. Song and J. Li, "Recent east experimental results and craft r&d progress for cfetr in china," *Selected Papers from the 30th IEEE Symposium on Fusion Engineering*, 2023, presented at SOFE 2023, see proceeding.

[6] Y. Sakamoto, "Strategy and progress of ja demo development," *Selected Papers from the 30th IEEE Symposium on Fusion Engineering*, 2023, presented at SOFE 2023, see proceeding.

[7] D. Brunner, "Commonwealth fusion systems' high-field path to fusion energy," *Selected Papers from the 30th IEEE Symposium on Fusion Engineering*, 2023, presented at SOFE 2023, see proceeding.

[8] A. Creely, "Operational plans for the sparc tokamak," *Selected Papers from the 30th IEEE Symposium on Fusion Engineering*, 2023, presented at SOFE 2023, see proceeding.

[9] M. Laberge, "Magnetized target fusion at general fusion," *Selected Papers from the 30th IEEE Symposium on Fusion Engineering*, 2023, presented at SOFE 2023, see proceeding.

[10] S. Woodruff and R. Miller, "Cost sensitivity analysis for a 100mwe modular power plant and fusion neutron source," *Fusion Engineering and Design*, vol. 90, pp. 7–16, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920379614005997

[11] S. Woodruff, J. K. Baerny, N. Mattor, D. Stoulil, R. Miller, and T. Marston, "Path to market for compact modular fusion power cores," *Journal of Fusion Energy*, vol. 31, pp. 305–316, 2012.

[12] S. Woodruff, R. Miller, D. Chan, S. Routh, S. Basu, and S. Rao, "Conceptual cost study for a fusion power plant based on four technologies from the doe arpa-e alpha program," 07 2017.

[13] H. Lux, D. Wolff, and J. Foster, "Commercialization of fusion power plants," *IEEE Transactions on Plasma Science*, vol. 50, no. 11, pp. 4401–4405, 2022.

[14] H. Wilson, I. T. Chapman, and C. Waldon, "One small step," *Nuclear Future*, pp. 46–49, 2020.

[15] M. Kovari, R. Kemp, H. Lux, P. Knight, J. Morris, and D. Ward, ""PROCESS": A systems code for fusion power plants—part 1: Physics," *Fusion Engineering and Design*, vol. 89, no. 12, pp. 3054–3069, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920379614005961

[16] M. Kovari, F. Fox, C. Harrington, R. Kembleton, P. Knight, H. Lux, and J. Morris, ""PROCESS": A systems code for fusion power plants – part 2: Engineering," *Fusion Engineering and Design*, vol. 104, pp. 9–20, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920379616300072

[17] S. I. Muldrew, H. Lux, G. Cunningham, T. C. Hender, S. Kahn, P. J. Knight, B. Patel, G. M. Voss, and H. R. Wilson, ""process": Systems studies of spherical tokamaks," *Fusion Engineering and Design*, vol. 154, p. 111530, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920379620300788

[18] J. Morris, S. Muldrew, P. Knight, M. Kovari, A. Pearce, S. Kahn, J. Maddock, T. Nunn, R. Chapman, C. Swanson, H. Lux, J. Foster, K. Ellis, M. Kumar, G. Turkington, J. Lion, S. Chislett-McDonald, A. Brown, J. Edwards, C. Ashe, E. Fable, K. Zarebski, C. Griesel, R. Kemp, S. Gubbins, S. Pickering, J. Matthews, G. Graham, C. Mould, T. Miller, S. Gadgil, D. Short, J. Cook, and P. Lloyd, "PROCESS," Sep. 2023. [Online]. Available: https://github.com/ukaea/PROCESS

[19] J. Keep, "The integrated step prototype powerplant," *Selected Papers from the 30th IEEE Symposium on Fusion Engineering*, 2023, presented at SOFE 2023, see proceeding.

[20] H. Lux, R. Kemp, D. Ward, and M. Sertoli, "Impurity radiation in demo systems modelling," *Fusion Engineering and Design*, vol. 101, pp. 42–51, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920379615302891

[21] H. Lux, R. Kemp, E. Fable, and R. Wenninger, "Radiation and confinement in 0d fusion systems codes," *Plasma Physics and Controlled Fusion*, vol. 58, no. 7, p. 075001, may 2016. [Online]. Available: https://dx.doi.org/10.1088/0741-3335/58/7/075001

[22] M. Siccinio, G. Federici, R. Kembleton, H. Lux, F. Maviglia, and J. Morris, "Figure of merit for divertor protection in the preliminary design of the eu-demo reactor," *Nuclear Fusion*, vol. 59, no. 10, p. 106026, aug 2019. [Online]. Available: https://dx.doi.org/10.1088/1741-4326/ab3153