Fusion Engineering and Design 190 (2023) 113544

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Technological features of a commercial fusion power plant, and the gap from DEMO

R. Kembleton [a,b,*]

[a] EUROfusion Consortium, Garching bei München, Germany
[b] Culham Centre for Fusion Energy, Abingdon, United Kingdom

A R T I C L E I N F O

Keywords:
Fusion power plant
Fusion commercialisation
Integrated operation

The future of nuclear fusion as a viable energy source has two major hurdles to overcome. Firstly, there are the daunting and complex technology and physics issues to be resolved before a power plant capable of breeding its own fuel and producing an excess of electricity can be built. Secondly, fusion must offer a useful and economically competitive product to energy markets worldwide, where it will compete with renewable sources and energy storage. However, that future energy market also places a premium on aspects of generation such as reliability of electricity delivery, and the avoidance of externalised costs which might arise from distributed generation such as wind farms or large-scale energy storage required to match seasonal variations in supply and demand. Fusion potentially has an advantage in these areas and an optimised environmentally-friendly energy system will need a mixture of technologies in order to be clean, reliable, cheap, and power-dense enough not to compete excessively for land.

DEMO will act as a technology demonstrator for a fusion power plant, providing relevant, *in-situ* proof of operation of materials and components, and of viable strategies for fuelling and component replacement. However, as a first of a kind and with inevitable performance margins built into the design due to the uncertainties associated with first integrated operation of all plant systems, DEMO will not be optimised for commercial availability or minimum electricity cost, but rather to produce the data required to achieve those in a full fusion environment. This paper reviews the features needed for commercial operation of a fusion plant, and how they can be achieved based on DEMO operational experience and parallel technology development.

1. Introduction

The potential basic parameters for a commercial fusion power plant cover a very wide range, from compact low aspect-ratio devices to advanced tokamaks based on high-performance plasma regimes, and the range of parameters for intermediate demonstration devices intended to prove the physics and technology performance span a similar range. The broad behaviour of plant systems and their interactions can be captured by a *systems code* [1,2] which can then be told to optimize the plant parameters and find a suitable operating point based on the physics and technology assumptions. However, decisions must first be made about what assumptions are reasonable, and what the target performance of the plant should be. These choices rely on extrapolations from existing knowledge and projections of what future energy markets may look like.

The drivers for fusion research are straightforward: the world must decouple the link between carbon emissions and energy generation; and the global energy market's value of ~$5tn/yr [3] is an attractive prospect for investors looking to profit from capturing part of it. As global development and progress proceed, energy demand, both for electricity and other fuels, is expected to continue growing.

In general, though, a commercial power plant must be reliable, inspectable, and maintainable. Reliability arises from predictable performance of components and materials in a realistic operating environment, and it is this fusion environment that DEMO (or a similar first-of-a-kind plant) uniquely provides. The data obtained on systems operation and stability in an environment with neutrons; fast neutrals; and typical thermal, stress, and chemical gradients is vital for future refinements and iterations of design. Lacking a truly representative

---

* Correspondence to: EUROfusion Consortium, Garching bei München, Germany.
E-mail address: richard.kembleton@euro-fusion.org.

https://doi.org/10.1016/j.fusengdes.2023.113544
Received 17 October 2022; Received in revised form 16 January 2023; Accepted 4 February 2023

environment in which to test components ahead of DEMO operation, it is extremely doubtful that an achievable optimised design will emerge first time: it will be difficult enough just to get everything to work together on the first attempt.

DEMO will also provide vital information into the ageing and lifetimes of components which may be permanent in DEMO but would require regular replacement in a plant intended to operate continuously for 40 or more years: this might include diagnostic elements and components open to but far from the plasma such as HCD systems, which will not receive a high lifetime dose of radiation or contamination during DEMO operation [4].

Some thought must therefore be put into how to best use the operational fusion environment provided by DEMO to test technologies intended to improve overall plant efficiency, test new materials, and assess the lifetimes of permanent installations through regular inspections. Tracking tritium migration and learning effective inventory management in a fully-operational electricity- and tritium-generating plant is also important. The operational plan of DEMO over its intended lifetime should be designed to fulfil these goals. In addition, there should be a deliberate programme to collect lessons learnt from manufacture of DEMO components, aimed at minimising material use and manufacturing complication and quantitatively assessing appropriate tolerances allowing effective assembly and operation of DEMO, which can be fed back into manufacturing plans for second-generation plants.

This paper outlines thinking with EUROfusion of how to approach the questions of the commerciality of fusion; where it sits within energy markets; and how to assess the remaining technology gaps between the current technology programme and a future fusion energy sector.

2. Energy market context for fusion

Any realistic model of commercial fusion roll-out has to assume it will be, at the least, several decades before fusion makes any substantial contribution to global energy supplies. In order to assess the market fusion will be operating in, and hence the expectations of potential customers, future market paths can be modelled [5] In addition, the impact of large-scale deployment of renewables and energy storage on grid reliability can be assessed [6,7]

Since, like renewables and also like fission, fusion is a capital-intensive form of energy generation – meaning that ongoing fuel and maintenance costs are a small fraction of the total investment – the price of electricity generated by fusion should be stable, unlike the volatility of fossil-fuel generation. Furthermore, fusion power generation is highly-predictable, in comparison to e.g. wind power.

These models tend to show that in scenarios that constrain carbon emissions, there is (a) a grid-optimising role for steady power production which allows a reduction in the overall energy storage and capacity needs of a pure renewable-and-storage grid meeting reliability goals, and (b) a cost competition for this role between fusion and other nuclear systems, due to their low carbon emissions. Therefore fusion does not compete on pure cost of electricity against renewable generation, but complements it, provided it has sufficiently high availability and energy density.

Electricity is not the only potential market for fusion, of course, although it is the most immediately-available one. As a thermal energy source, fusion heat can be used for a wider range of processes, from desalination and disctrict heating up to synthetic fuel production and other chemical processes. Ultimately this may require new materials to take advantage of higher temperatures, and plant redesign for process chemistry, but these applications are also future possible application for fusion [8]

The other part of the market context is what size of unit markets will bear. Studies have previously shown that, in general, cost of electricity falls with increasing unit size, but ultimately no-one is going to pay more than a few tens of billions of Euros for a single power station (e.g. Hinkley Point C). In addition, grid stability studies [9] put a cap on the level of power that can suddenly be removed from the grid – in the event of a plasma disruption necessitating shutdown, for example – of about 1.5GW. Taking all these considerations into account, it is reasonable to consider units of 1GW at a maximum price of €10bn/GW as the target for fusion power plants. For comparison, large (MW) scale wind turbines in 2022 cost around €2bn/GW of installed capacity (including project costs) [10] although the intermittent nature of their generation means that they play a very different role in the grid.

3. High level requirements for DEMO

EU-DEMO has a small number of high-level objectives: to produce substantial net electricity, to be tritium (T) self-sufficient, and to demonstrate the successful operation of (all) power-plant-supporting technology [11] The expansion and interpretation of these requirements, in the context of the current technology choices for EU-DEMO, leads to the design point given in Table 1.

DEMO is intended to be a (relatively) low-risk power plant prototype based on the best currently-available data in physics and technology. It is closely attached to the ITER timeline, and aims at comprehensively closing many technical gaps simultaneously, meaning conservatism is designed in to many system performance targets so there is margin for underperformance. This tends to lead to a large, conventional device [14]

In addition to these goals DEMO must breed and store enough excess tritium to start-up second-generation fusion plants.

A tokamak power plant is a highly-complex and integrated system. Only by approaching it as a real engineering project that is intended to be built can the integration issues and trade-offs really be identified.

4. Features of a commercial power plant

When considering the technology choices and performance targets of a commercial fusion plant concept, expectations of the timescale to completion – and hence maturity of technologies and market penetration – and the roles played in the wider energy market must be clearly defined. Variations in these assumptions lead to (often very) different concepts and technology paths to their realisation [15].

In particular the market assumptions that matter are the target size of a unit – and hence the position in the capital cost/cost of electricity tradeoff curve it occupies; the operation of the unit (can it be pulsed? must it have sufficient flexibility for some load-following?); and the purpose of unit (purely electrical, or also thermal?).

Table 1
EU-DEMO Physics Baseline 2018 relevant machine parameters, produced by the systems code PROCESS [12] Comparisons are made with the ITER $Q = 10$ scenario [13].

	DEMO	ITER
Major and minor radius, R, a [m, m]	9.0, 2.9	6.2, 2.0
Aspect ratio, A	3.1	3.1
Field on axis, B_0 [T]	5.86	5.3
Plasma safety factor, q_{95}	3.89	3.0
Triangularity, elongation, δ_{95}, κ_{95}	0.33, 1.65	0.33, 1.65
Plasma current, I_P [MA]	17.75	15.0
Non-inductive current fraction, f_{NI}	0.39	
Driven current fraction, f_{CD}	< 0.05	
Fusion power, P_{fus} [MW]	2000	500
Power across separatrix, P_{sep} [MW]	170.4	
LH threshold power, P_{LH} [MW]	120.8	
Confinement H-factor, H_{98}	0.98	1.0
Electron density, $<n>/n_{GW}$	1.2	0.85
Average temperature, $<T>$ [keV]	12.49	
Normalised beta, β_N [% mT/MA]	2.5	1.8
Z_{eff}	2.12	
$P_{sep}B/q_{95}AR$ [MW T/m]	9.2	9.2
P_{sep}/R [MW/m]	18.9	
Pulse length [sec]	7200	3000

After these points, the main element that matters is how high reliability and availability are achieved. These factors are critical. The facility must be designed for maintenance from the outset, and this implies a high degree of modularisation in the componentry so that failed components can be swapped out with minimum downtime. This overlaps with a target of having the componentry as designed-for-manufacture as possible so that sub-assemblies are also modular and can be mass-produced. Finally, continuous operation is key: sufficient whole-plant diagnostics must be present to monitor the state of the plant and plan preventative maintenance, and maximising the reliability of all subsystems is also vital.

For comparison of the reliability step required, ITER might reach one full year of plasma operation over lifetime, compared to maybe 5–10 years of full power operation in DEMO or a first of a kind (FOAK), and 30–50 years in a power plant operating at commercial availability.

5. Gaps from DEMO to commercial fusion

Many of the gaps from DEMO to a commercial fusion plant revolve around the fact that, before DEMO (or a DEMO-class device) is built and operational, there is no large-scale fusion-representative environment in which to test components at full scale prior to deployment. Some testing can be done on a limited scale – for example materials qualification in IFMIF-DONES, and the test blanket modules (TBMs) in ITER – but overall fusion technology probably remains only partially fully-qualified until DEMO is actually operating at full fusion power. This intersects with a certain amount of risk-aversion, where there is a reluctance to proceed onto the next stage of the programme until performance can be guaranteed, but that performance cannot be guaranteed without the next device being built to test the components.

Particularly in-vessel components like the blankets and divertor will be subject to large temperature and stress gradients, and to bulk heating and material damage from neutrons. The effect of these combined loads, including over planned component lifetimes, is especially hard to experimentally test at reduced scale and limited dose. It is also vital that the TBM programme and DEMO rapidly prove the achievability of a closed tritium cycle, as (D-T) fusion is unsustainable without this.

Next, a fusion power plant needs to be a relatively simple proposition for the operator, although complex under the hood. All systems – including the plasma – must be reliable and robust, with predictable maintenance cycles. Achieving this state may well require multiple iteration cycles with testing. Potential failure modes need to be designed in to protect the core of the machine, which may, for example, mean more limiters for first-wall protection, with a consequent impact on tritium breeding. To appropriately find the trade-off between these factors requires actual operation experience of both plasma operation and tritium breeding.

These technology gaps, then, mainly revolve around identifying the true performance envelope for the components in a genuine fusion environment, and using that information to eliminate excessive operational margins and overspecified designs. Once we have this data, designs can be re-optimised to be closer to commercially-viable designs.

For a commercial plant availability is a key attribute. Downtime for post-incident inspections costs money directly, even before any component replacements that may be required. DEMO, by contrast, should expect such regular interventions and sample-taking because it is collecting data on component and material lifing as part of its core mission to provide the engineering basis for commercial plants.

To shape the direction of research aimed at closing the gaps it is useful to consider concept plants and their required performances. For this purpose three options are considered.

A **near-term** (and hence DEMO-like) tokamak: this would feature pulsed operation with a DEMO-like plasma, providing ~1 GW average net electrical power to the grid. To make this a viable prospect, we need an improved pulse length over DEMO's 2 h, better plant efficiency to reduce the internal recirculating power P_{recirc}, improved thermal efficiency η_{th}, and an availability of over 70%. This option probably also needs substantial on-site energy storage to smooth the inter-pulse ebb and flow from the grid. We have to assume the grid itself is robust and probably has bulk energy storage available as well. The capital cost of the plant must be reasonable.

A **long-term** (steady-state) tokamak: avoiding pulsing means that the plant life-time is extended due to the elimination of fatigue concerns from repeated frequent variations in forces and temperatures. However, to support this, an advanced plasma scenario offering higher f_{BS}, improved η_{th}, and much greater efficiency in auxiliary current-drive systems are needed. As the heating and current-drive (HCD) systems will be in near-continuous operation, this also places high reliability and maintainability requirements on them. The improved thermal efficiency requires materials developments to expand the operating temperature range, and it is likely that divertor protection becomes even more challenging.

The final option is a **stellarator** power plant, which is intrinsically steady-state and requires no continuous current drive, easing the recirculating power requirements. The major radius of this option is large, but the high aspect ratio and absence of PF coils means that although the coil shapes are complex, their sizes become more tractable for bulk manufacture. The gaps here are the development of a blanket and divertor maintenance concept, the design and manufacture of high-field coils with complex 3D geometry, a reliable power-plant scale physics basis, and an exploration of the very large potential design space for stellarators to identify the critical system interactions and compromises for a power plant.

There are of course many other potential configurations, for example those based on spherical tokamaks [16,17] as well as a variety of different plasma pinches, magnetic mirrors, and inertial confinement approaches [18] The concepts described above are just those used within EUROfusion to model technology gaps and market performance. These draw upon previous studies, especially the European Power Plant Conceptual Study (PPCS) [19] it is also worth mentioning the comprehensive ARIES-AT [20,21] study from the US and the FFHR stellarator study from Japan [22]

6. Making the most of DEMO

While DEMO's headline mission is to illustrate the achievability of generating fusion electricity in a self-sustaining and maintainable way, it has a long potential lifetime beyond this and it is reasonable to ask, beyond electricity generation and T production, what materials/component/other data can be gained during DEMO operation that commercial plants cannot deliver?

DEMO provides a true fusion test environment which can provide data for component lifing and performance. In particular, this has implications for the plant layout (there should be hot cells for materials science on-site, for example) and operation. Plans should be made for incorporating a materials surveillance scheme, meaning withdrawal of samples at intervals for monitoring, along with comprehensive coverage of irradiation conditions and temperatures. DEMO should also provide data to assess how the output of critical diagnostics change over time and the likely impact this has on plant operation and maintenance – here the idea of a "digital twin" is particularly attractive, but such a twin must be calibrated.

DEMO will also help to refine preventative maintenance schedules. Its design, build, and operation will help to define the regulatory regime for future fusion devices. As the first of a kind it will establish fusion supply chains, and there will be lessons learned from its assembly and commissioning. "Commissioning" in this case is not just to first plasma start up: since many of the systems are new technology this also covers heat extraction, tritium generation and separation, testing of RM equipment, formalisation of standard operating procedures, plant shutdowns…

All of these tasks form part of the overarching mission of DEMO and time taken for the data collection here is productive time: the “availability” of DEMO is not just the time spent producing electricity. In addition, the management of knowledge from the whole DEMO programme is critical.

Fusion is currently a relatively small industry, and although there is a generation of engineers who have brought ITER to realization, if the DEMO-EDA starts too long after ITER is delivered this highly-skilled and experienced workforce will be lost to other industries due to lack of opportunity within fusion. Furthermore, ITER has worked to involve and scale-up industrial partnerships around the world in fusion materials and technology. This interest and expertise would also be lost in the event of a long delay between ITER and DEMO.

7. Conclusions

As fusion continues to move towards a first electricity-generating plant, it is important to keep a commercial future role in mind to ensure that the correct data is collected. There are a wide range of possible plant concepts, depending on the assumptions made about the future energy market, the readiness of given technologies and plasma scenarios, and time taken to develop and test those technologies in the interim.

The success of fusion is reliant on a healthy and diverse research environment which embraces multiple approaches, learning from one another. It is important to build and operate target technologies to develop them as rapidly as possible so they can be considered for practical integration into plant concepts.

Future power plant designs will inherit the systems – including licensing regimes – and tools that we build today for design integration and development: we need to make sure that justifications for design decisions are passed on in such a long-term research effort, and that the tools are flexible enough to allow for reintegration as new information becomes available.

The critical long-term goal in developing commercial options is the reliability and manufacturability of all plant systems and components. This requires a fusion environment for development and qualification. It also leans towards modularity in all systems for rapid maintenance and mass production. Supporting research, including at DEMO longer term, needed to develop these capabilities

Finally, electricity is not the only market for fusion, but it is the most immediate one and therefore the most promising for near-term options.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

[1] M. Kovari, R. Kemp, H. Lux, P. Knight, J. Morris, D.J. Ward, PROCESS”: a systems code for fusion power plants—Part 1: physics, Fusion Eng. Des. 89 (12) (2014) 3054–3069.
[2] M. Kovari, F. Fox, C. Harrington, R. Kembleton, P. Knight, H. Lux, J. Morris, PROCESS”: a systems code for fusion power plants – Part 2: engineering, Fusion Eng. Des. 104 (2016) 9–20.
[3] Businesswire, “Global energy consumption market to 2025,” 22 October 2021. [Online]. Available: https://www.businesswire.com/news/home/20211022005449/en/Global-Energy-Consumption-Market-to-2025—Featuring-Tokyo-Gas-BHP-and-Iberdrola-Among-Others—ResearchAndMarkets.com. [Accessed 16 January 2023].
[4] G. Federici, et al., DEMO design activity in Europe: progress and updates, Fusion Eng. Des. 136 (2018) 729–741.
[5] H. Cabal, et al., Fusion power in a future low carbon global electricity system, Energy Strateg. Rev. 15 (2017) 1–8.
[6] F. Wagner, Electricity by intermittent sources: an analysis based on the German situation, Eur. Phys. J. Plus 129 (2012) 2014.
[7] F. Romanelli, Strategies for the integration of intermittent renewable energy sources in the electrical system, Eur. Phys. J. Plus 131 (2016).
[8] T. Griffiths, R. Pearson, M. Bluck, S. Takeda, The commercialisation of fusion for the energy market: a review of socio-economic studies, Prog. Energy 4 (2022), 042008.
[9] S. Takeda, et al., Limitation of fusion power plant installation on future power grids under the effect of renewable and nuclear power sources, Fusion Eng. Des. 109-111 (2016) 1754–1758.
[10] Renewables First, “How much does a wind turbine cost?,” [Online]. Available: https://www.renewablesfirst.co.uk/windpower/windpower-learning-centre/how-much-does-a-wind-turbine-cost/. [Accessed 16 January 2023].
[11] T. Donné, European Research Roadmap to the Realisation of Fusion Energy, EUROfusion, Munich, 2018.
[12] R. Kembleton, J. Morris, M. Siccinio, F. Maviglia, the PROCESS team, EU-DEMO design space exploration and design drivers, Fusion Eng. Des. 178 (2022), 113080.
[13] Assessment of the baseline scenario at q95~3 for ITER, Nuclear Fusion 58 (12) (2018), 126010.
[14] R. Kemp, R. Wenninger, G. Federici, H. Reimerdes, R. Ambrosino, R. Brown, M. Coleman, Exploring a broad spectrum of design options for DEMO, Fusion Eng. Des. 136 (B) (2018) 970–974.
[15] R. Kembleton, A.W. Morris, G. Federici, A.J.H. Donné, Design issues for fusion commercialization, IEEE Trans. Plasma Sci. 48 (6) (2020) 1703–1707.
[16] B.N. Sorbom, et al., ARC: a compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets, Fusion Eng. Des. 100 (2015) 378–405.
[17] UKAEA, “Spherical tokamak for energy production (STEP),” [Online]. Available: https://step.ukaea.uk. [Accessed 16 January 2023].
[18] Fusion Industry Association, The Global Fusion Industry in 2022, Fusion Industry Association, Washington, 2022.
[19] D. Maisonnier, et al., DEMO and fusion power plant conceptual studies in Europe, Fusion Eng. Des. 81 (8–14) (2006) 1123–1130.
[20] C.E. Kessel, et al., The ARIES advanced and conservative tokamak power plant study, Fusion Sci. Technol. 67 (1) (2015) 1–21.
[21] F. Najmabadi, et al., The ARIES-AT advanced tokamak, Advanced technology fusion power plant, Fusion Eng. Des. 80 (1–4) (2006) 2–23.
[22] T. Goto, et al., Conceptual design of a compact helical fusion reactor FFHR-c1 for the early demonstration of year-long electric power generation, Nucl. Fusion 59 (7) (2019), 076030.