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RESEARCH

Developing Integrated Cost Models for Fusion Power Plants

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Abstract
Systems models and associated cost analyses are widely used within the fusion community to analyse tokamak designs, from prototype and demonstrator machines to potential commercial fusion power plants. To ensure the design programmes of fusion prototype/demonstrator power plants deliver a cost optimised design (within existing uncertainty limitations) the use of integrated cost modelling during the design process is essential. This integration produces holistic solutions in which engineering design choices and changes are directly represented in the cost results, allowing alternative solutions to be tested technologically and financially in the same analysis and cost estimates to be directly aligned with each specific design solution. Using examples from the STEP (Spherical Tokamak for Energy Production) programme this paper shows how implementing such an approach allows an interrogation of the design through the lens of cost-effectiveness, enabling a systematic exploration of potential trade-offs between performance and cost, highlighting cost drivers and interrogating the design aspects underpinning them, and facilitating holistic comparisons between design options. Including cost analysis into early design decisions through integrated cost modelling will drive a cost-optimised design; this is vital in proving that fusion power plants can be an economically viable energy source. One top-level example of this approach is understanding the critical size drivers and therefore cost drivers of the design, such as the inboard radial build for the STEP design. This understanding enables optimisation of this parameter within the relevant margins required to ensure performance (within design uncertainties).

Keywords Spherical tokamak · Cost analysis · Fusion technology

Introduction

Complex, multi-disciplinary engineering programmes benefit from the application of integrated design, a holistic design approach that encompasses the whole life cycle of the programme, from concept, through construction, operation, and decommissioning [1]. This holistic view allows early design decisions to be informed by plans for later processes; for example, site selection based on likely component size and transportation access; or materials down-selection to take into account any necessary decommissioning cost and time burden. A broad view of such a programme also facilitates early categorisation of interfaces and system interactions, with the opportunity to capture potential emergent behaviours that can arise when multiple systems are integrated into the final piece.

Fusion is intrinsically a highly integrated technology; the application of integrated design is therefore more important within fusion projects than for projects that are able to tolerate the separation or modularisation of some (or all) discrete sub-systems. This holistic approach becomes crucial when the project under development is a fusion power plant rather than a smaller plasma physics experiment: in a power plant the number of integrated systems is greater, and the required level of integration may also be more involved.

As complex systems increase in size they increase in cost, and in mega-projects – a category of programme that includes fusion power plants as well as similar ventures in more mature industries [2] – this is not only as a result of increases in material and manufacturing costs but also through increased complexity associated with management, procurement, and supply chains.

To ensure that a planned fusion power plant is cost competitive within the wider energy industry, decision-makers

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need to understand the cost implications of design decisions and be able to identify cost drivers in the design. Integrated cost modelling and analysis is essential for such an approach. As a novel technology entering a mature energy market, fusion cannot afford the luxury of cost complacency [3]. Fusion needs to be cost-effective and economically viable in a way that has not previously applied to emergent energy sources such as fission [4] – or even to the early years of renewable energy technologies [5]. Demonstrating commercial viability is currently one of the major challenges in the developing fusion power industry, close behind the demand to demonstrate the feasibility of fusion as a reliable producer of electricity (or alternative useable energy, e.g. heat).

Systems modelling is widely used within the fusion community to analyse prototype and demonstrator power plant designs in early, (pre-)concept design phases, with multiple systems codes currently in use and development, including SYCOMORE in use on EU-DEMO [6], PROCESS [7, 8] and GASC [9] used to assess CFETR [10, 11], the ARIES systems code [12], and TPC [13] used on JA DEMO [14].

Both parallel to and integrated with these systems codes, a number of cost analyses exist in the literature around prototype and demonstration plants, such as a pilot compact plant [15], a ‘generic fusion reactor’ [16], and the demonstrators EU-DEMO [17] and Demo-CREST [18].

Potential commercial fusion power plants have also been considered, including a ‘DEMO-like’ plant modelled in the FRESNO code [19], an exploration of the cost of electricity produced by an inertial fusion power plant [20], and a study encompassing a range of near- and advanced-technology plants [21].

However, the author is not aware of any publications that specifically highlight the impact of incorporating cost estimates as a key measure in integrated design decisions, i.e. during the design process, within the fusion community.

This work describes the cost integration in the design methodology in UKIFS’s STEP programme (Sect. "STEP Integrated Costing Methodology") and then discusses examples of integrated cost calculations developed within the concept design phase (Sect. "Results and Discussion"), highlighting the value of applying this approach at both system and whole plant level, before drawing conclusions (Sect. "Conclusion").

STEP Integrated Costing Methodology

The engineering approach across the STEP (Spherical Tokamak for Energy Production) programme [22] is one in which a broad design space is explored, multiple potential solutions are identified and evaluated, and then the preferred solutions are selected and progressed into more detailed design stages [23]. This design progression was initially guided and gated using defined Concept Maturity Levels (CMLs) [24], a framework designed for tracking and communicating design maturity in the early stages of engineering projects.

The systems code utilised within the STEP programme is PROCESS [7, 8]. This UKAEA-owned systems code incorporates multiple unique cost models, the inputs of which are closely coupled with the outputs from the physics and engineering models. The system code output is therefore a solution that is not only a physically consistent design of an integrated fusion power plant, but one which also generates the cost estimates supporting that specific solution. Alternative design solutions can hence be tested technologically and economically in the same simulation.

The PROCESS code can be used to design and analyse multiple different fusion power plant concepts (an example is the cost sensitivity studies of the EU-DEMO concepts [17]). The early inclusion of cost analysis within any fusion programme will support decision-making activities both in economically-driven discussions and technical comparisons, as well as in areas where there is apparent tension between cost and performance. This integrated modelling approach particularly supports the STEP programme’s systematic exploration and evaluation of multiple solutions by facilitating analysis and interrogation of multiple cost estimates; as engineering and technology options are identified, the cost implications of each of the potential solutions can be assessed.

Such an assessment is holistic and can be explored at both the system level and the integrated solution level. System-level results include estimating cost deltas between specific technology selections; the integrated solution-level estimates can identify how proposed engineering changes within a single system, or a single design parameter, may have wider-ranging impacts (both in whole plant results and in cost estimates) than is immediately evident.

The wider STEP costing methodology has been described in [25], while the approach to dealing with uncertainties is detailed in [26] and corrections to total programme cost estimates from reference class forecasting (RCF) are discussed in [27]. For the purpose of making design decisions, absolute costs (and therefore corrections from RCF) are not relevant but *relative* costs are, and uncertainties of estimates must be understood in order to not over-interpret the results. Especially in the early stages of the design it is critical that trends in cost data are seen and interpreted within the simplicity of the models and the large uncertainties in the data.

Results and Discussion

Technology Cost Differentials

Integrated cost modelling facilitates the consideration of system/sub-system cost in discussions around technical trade-offs or solution down-selection, in much the same way as aspects such as complexity and manufacturability can be considered.

During the concept design phase for the STEP Prototype Powerplant, two preliminary options were developed for the magnetic confinement system: Design 1 used Cryogenic Aluminium and Design 2 used High Temperature Superconductor (HTS) tape as the conductor (e.g. REBCO or a similar material). System code requirements were developed for each design and integrated solutions generated, including cost estimates. (This analysis did not also include Low Temperature Superconductor (LTS) material as an option for the STEP magnets; LTS had already been excluded from the concept design on technical grounds.)

While an isolated comparison of the material costs of the designs would indicate Design 1 is a more economically favourable choice, as the material costs are a fraction of those in Design 2, the coupling of the cost model with the full engineering simulation of each tokamak design enables a more holistic view, demonstrating that material (and associated manufacturing) costs are only a component part of the complete costs of either design choice.

The coupling of the cost model with the multiple relevant engineering models allows a full calculation of the total cost difference between options: this wider view incorporates the costs associated with systems necessary to support the primary magnetic confinement components during plant operation, such as power supplies and cryogenic systems. Of particular note in this example is that the demands on the relevant cryogenic systems are considerably higher for Design 1 than for Design 2, and hence the costs are higher; when this supporting system cost is incorporated into the holistic view of the magnetic confinement costs, the two design options are much more comparable in total cost (Fig. 1).

This result demonstrates that when the cost estimates for this system correctly incorporate all the relevant elements of the integrated solution, there is not a strong economic differential between these proposed design options. This is compounded when it is understood that the uncertainties in early concept design stages of programmes can be within a range of −50% to + 100% [26].

In the context of the STEP programme, this holistic cost analysis supported the continued exploration of a broad design space for a magnetic confinement system. Having cost estimates for solutions at an early stage in the design process can highlight potentially counter-intuitive or overlooked interactions between system elements, preventing the premature exclusion of specific design paths from further assessment.

Power Plant Economics

It can be the case that a single component or sub-system has an outsize influence on the efficiency, operational availability, or final power output of a fusion power plant. In this situation the impact of that element on the cost (and cost-effectiveness) of the entire machine must be accounted for – and this can be drawn out through integrated cost modelling.

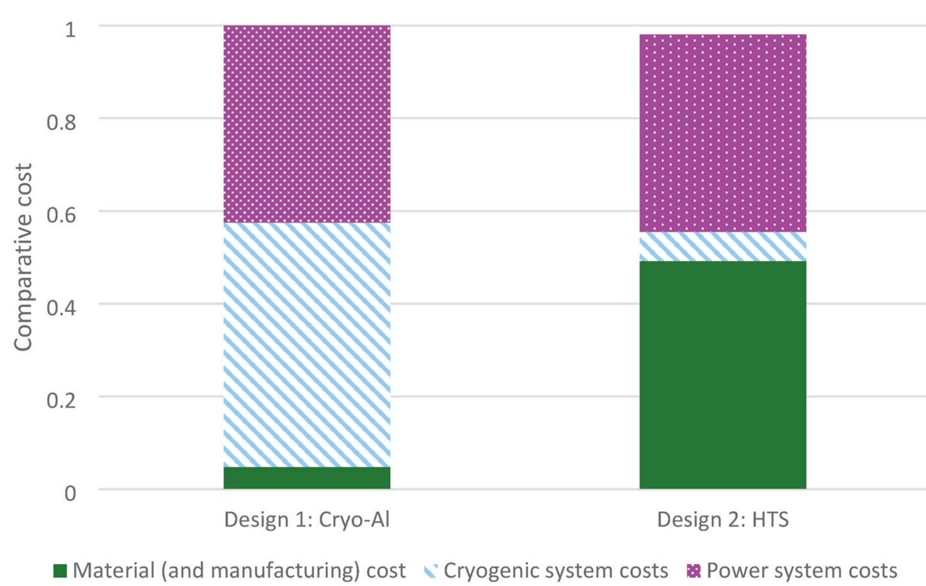

Fig. 1 Example of a system-level assessment of comparative cost: two designs of tokamak magnetic confinement systems

The low aspect ratio of the spherical tokamak design is as much a benefit as the compact overall size. The plasma within a spherical tokamak is naturally more elongated than that in a conventional aspect tokamak; as well as granting better vertical stability [28], this greater elongation results in improved efficiency of the plasma (through higher plasma current and increased confinement time) [29]. A more efficient plasma ultimately results in the power plant supplying more output electrical energy to the national power grid, for a given energy and fuel input. This is aligned with work for conventional aspect ratio tokamaks, where elongation has been shown to be a significant factor impacting the net electric power produced in a tokamak of a fixed size [30]. Ultimately, a more efficient plasma will result in a more energy efficient fusion power plant, which is the realisation of a more cost-effective solution.

When cost models are integrated into the physics and engineering models that encompass the entire power plant, any modifications applied to systems that affect the plasma efficiency will propagate through to calculations supporting whole plant economic estimates, including output metrics such as the Levelised Cost of Electricity (LCOE). The impact (positive or negative) of such modifications will be represented in the output cost and economic estimates, and systems with unexpected or outsize influence on the plant cost estimates can be traced and tracked.

As the largest consumer of recirculated power, the auxiliary Heating and Current Drive (HCD) is one of the most important systems to consider when assessing plant power use, and the performance of this system is key in driving overall fusion plant efficiency [31].

The STEP prototype HCD will be a microwave only system [32]; a crucial factor in this technology selection was the high efficiency possible, and the improvement this brings to the delivered integrated solution. Studies extrapolating spherical tokamak designs to commercial power plants show how critical it is to reduce the amount of recirculated power needed to assure commercial viability of fusion. Impacts of changes in the efficiencies of the HCD system have been highlighted in [26].

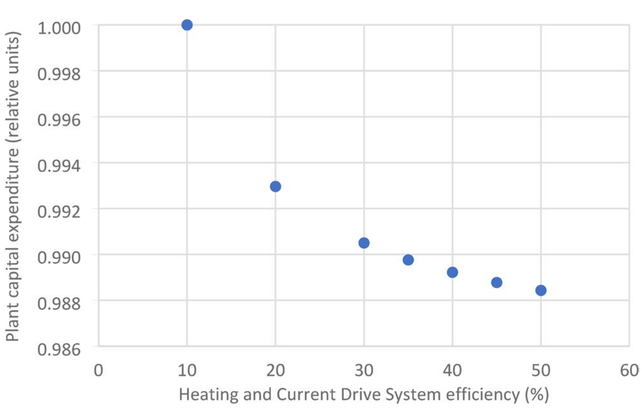

Fig. 2 Integrated cost model results for multiple systems model solutions for a proposed fusion power plant, implementing different efficiencies of HCD

Modelling potential improvements in HCD efficiency within the PROCESS system code [7] allows exploration of the impact of this system on overall plant cost. For a more efficient HCD system, the required plasma current can be driven using a lower input power; this results in a higher proportion of output fusion energy being available for electricity generation and ultimately a higher energy output from the plant.

Therefore, as HCD system efficiency increases, the plant becomes more efficient overall: the model shows a reduction in the total expenditure required to meet the power plant's energy output targets (Fig. 2). Improvements in a single aspect of this key fusion system will result in a more cost-effective fusion power plant. It is important to note that even modest relative reductions in expenditure may be considerable when the total cost of a power plant might approach many billions in cost (e.g. EUR35bn [33]).

Radial Cost Impact

Size is an important cost driver for fusion power plants [8]; one expected benefit of the spherical tokamak design over a conventional aspect ratio tokamak is that the device can be more compact [34], but size still remains a key consideration. During the concept design phase of the STEP programme the inboard radial build, i.e. the radial distance from the device vertical centreline to the inner plasma edge, was identified as the major size driver for STEP.

A larger inboard radial build results in a larger tokamak, and hence higher cost estimates. However, if the increased inboard radial build includes thicker shielding layers between the plasma and key inboard components, those components will experience reduced irradiation and consequent increased operational lifetimes [35]. Longer component lifetimes can reduce planned maintenance costs (i.e. repair and replacement costs) through the plant lifetime.

Systems codes can utilise engineering models related to power and heat generation to calculate estimates of neutron loading and heat flux at different locations within the tokamak; combined with known material damage limits, system models can estimate the lifetimes of specific replaceable parts in a particular design solution [8]. Integrated cost models can then produce cost estimates associated with the consequent rate of replacement parts required through the anticipated lifetime of the plant.

An integration analysis of STEP's spatial envelope explored the impact on whole plant cost estimates of increasing the inboard radial build size, utilising the PROCESS system code. The results demonstrate that increasing

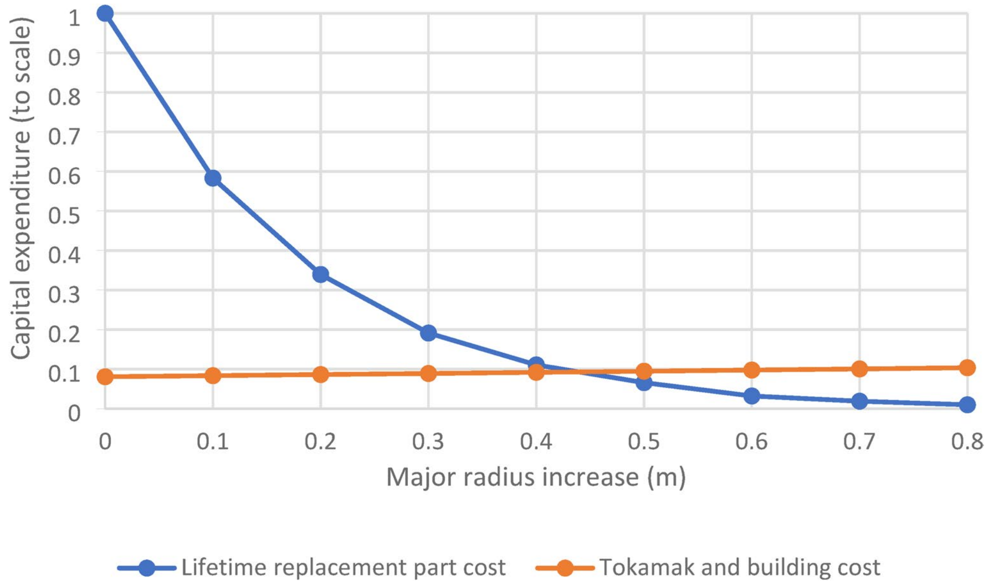

Fig. 3 Example of the potential capital cost impact of increasing major radius on tokamak (machine and building) costs due to higher replacement parts costs incurred by lower radial size designs. (Cost units not disclosed due to commercial considerations.)

the tokamak radial build (shown in terms of the major radius, the radial distance from the device vertical centreline to the plasma centre) drives an increase in tokamak capital expenditure cost (machine and associated building cost) but produces a reduction in through-life replacement part costs (Fig. 3); fewer replacements are required due to the longer lifetime of the components.

It should be noted that this analysis was performed at a high level and on an early concept design. These results represent a non-optimised design across all elements, including relatively simple shielding and monolithic replacement parts. A more detailed, optimised design could be expected to show a less dramatic initial cost for replacement parts due to better shield design and better part design; for example, modularisation of components may allow portions of damaged components to be replaced rather than an entire component, reducing the cost of each replacement.

However, the integration of cost models with engineering models allows for this type of comprehensive assessment of the true cost trade-off between these elements of spherical tokamak design: comparing the increase in capital costs with increased tokamak size, and the reduction in through-life costs due to a lower component replacement rate (or, potentially, decreased capital costs at the expense of increased through-life costs). More advanced component designs can be implemented within the system code as they are developed and modelled, allowing repeated comparative analyses of this trade-off as the plant design develops.

Conclusion

Early inclusion of cost analysis in design decisions ensures a cost-optimised design at both individual system and whole solution levels. Due to the highly integrated nature of fusion power plants, cost optimisation of such programmes can only be achieved through a holistic approach to cost estimation that uses integrated cost modelling. This approach can assist in design space exploration, support the identification and analysis of cost drivers, and be used to interrogate systems elements in potential trade-offs between performance and cost.

This paper has summarised how size, as a significant cost driver for tokamak power plants, can be optimised through manipulating the inboard radial build on smaller spherical tokamaks, has discussed the impact of Heating and Current Drive efficiencies on whole plant costs, due to the system's role as the largest consumer of recirculating power, and has demonstrated the importance of a holistic approach to cost assessments when making design decisions such as magnetic components' conductor materials.

Embedding cost models within systems codes, and thereby providing cost estimates associated with multiple integrated engineering solutions, also provides a foundation for establishing a cost-conscious culture in an engineering programme. This benefits any complex, multi-disciplinary programme, and will be particularly crucial for the first generation of fusion power plants aiming to prove that this technology is an economically viable alternative to existing energy sources.

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Declarations

Competing Interests The authors declare no competing interests.

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