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Nousheen Nawal, Hanni Lux, Member, IEEE, Rhian Chapman, James R. Cowan, Member, APM

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Fusion Power Plant Cost Modeling Uncertainties

Nousheen Nawal, Hanni Lux, *Member, IEEE*, Rhian Chapman, and James R. Cowan, *Member, APM*

***Abstract*— Being a novel technology, estimating costs for fusion power plants comes with large uncertainties. Cost uncertainties in prototypes arise from various sources and reduce with programme maturity (including the selection of a site), technical and design maturity as well as the maturity of the commercial strategy (e.g., make vs. buy decisions, partnering decisions). In the early design phases, where not much detail is fixed, cost is typically evaluated via analogy/comparator to existing technologies, which are typically associated with high uncertainties due to the innovative nature of fusion technology. Early cost estimates for fusion power plants are broken down using a top-level cost break down structure as this allows for cost uncertainty evaluation over the various fusion components. The STEP prototype fusion power plant is nearing the end of conceptual design with significant uncertainties but seeks to follow best practices to effectively manage costs. Best practice in cost estimating involves evaluating the base cost estimate, corresponding uncertainties, project risks, and correcting for optimism bias as defined by the IPA. The overall objective is to illustrate the importance of uncertainty definition within fusion prototype/demonstration powerplants and their impact on programme costs.**

***Index Terms*— Costs, Fusion power generation, Uncertainty**

I. INTRODUCTION

Fusion is an emerging energy technology, hoping to globally transform the energy sector once commercialized, with both government and private investment at an all-time high [1]. For fusion energy to attain recognition as a viable sustainable solution, it requires cost competitiveness. Many prototype/demonstrator fusion power plant programmes are in their conceptual or early engineering design phase [2] [3] [4], which is an ideal time to influence the cost of the final product [5]. However, due to its First-Of-A-Kind (FOAK) nature and nascent supply chain, cost uncertainties are inevitably large. Therefore, it is prudent to both understand their magnitude, distribution, and sources, as well as having a clear strategy to reduce these cost uncertainties as the respective programmes mature.

Some work to estimate the costs of prototype/demonstrator/commercial fusion power plants has been published in the past [6] [7] [8] [9] [10], however, due to the early stages, no uncertainty evaluations for costs have been conducted. Typically uncertainty evaluation and propagation for fusion power plant design has been restricted on evaluating the impact of engineering or physics uncertainties on outturn performance, if the plant was built in line with its current design [11] [12] [13] [14].

The STEP programme, which aims to design and build a prototype fusion power plant that can provide net energy into the national grid of circa 100 MWe [15] is nearing the end of its conceptual design phase, transitioning into its engineering design. As such there are significant design, engineering, construction and hence cost uncertainties prevalent at this time. In this work, we discuss both generic best practice around cost uncertainty methodology as well its application to the STEP programme.

We begin by discussing the various sources of uncertainties for large progammes in Section II. We then consider the best practice of evaluating uncertainties in cost estimation and how they are expected to reduce over a programme's lifecycle in Section III. In Section IV we discuss the application of cost uncertainties in STEP as an example of a current prototype fusion power plant programme at the end of its conceptual design stage. We conclude in Section V.

II. SOURCES OF COST UNCERTAINTIES

To quantify these cost uncertainties at such an early stage of development, a strategic approach must be taken to first understand all the possible sources of uncertainty and their impact.

The AACE Class Estimate System [16] is an effective tool for managing cost uncertainties over time. This system categorizes project definition levels into five distinct classes, with Class 5 having the lowest level of definition and Class 1 having the highest. Initially, FOAK fusion projects at Class 5 rely on general benchmarks and expert opinions, leading to significant cost uncertainties. However, as the project progresses through Classes 4, 3, 2, and ultimately reaches Class 1, the level of project definition and accuracy of cost estimation greatly improve. We can attribute this class system to sources to formulate a strategy and allow for effective management of cost uncertainties through a project's lifecycle.

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Nousheen Nawal, Hanni Lux, Rhian Chapman and James R. Cowan are with UKAEA (United Kingdom Atomic Energy Authority), Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK (Corresponding Author e-mail: Nousheen.Nawal@ukaea.uk).

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A. Programme Maturity

In FOAK fusion projects, uncertainties in cost estimation are notably influenced by the level of programme maturity. At the early stages of a programme, stakeholder expectations may not yet have been sufficiently defined, and early requirements are often subject to change as objectives and solutions emerge.

Programme planning is the essential basis for effectively dealing with these uncertainties in a big project. Its main goal is to systematically advance programme development. The programme schedule plays a crucial role in estimating indirect costs associated with activities such as project management, administration, support services and any other standing-army resource type. When there are delays or extensions in the project schedule, the duration over which such costs are borne also increases; leading to significant cost of time delays increases. Uncertainties related to other schedule changes can affect the overall cost estimation and budgeting process.

A prime example is the process of site selection. The selection of a suitable site for a fusion power plant involves geological, environmental, and regulatory considerations, which can introduce uncertainties in estimating costs and can vary widely between potential sites. A further classification of estimates is presented in Table 1.

Estimate classification	Class 5	Class 4	Class 3	Class 2	Class 1
Project description	General	Preliminary	Defined	Defined	Defined
Target operating model	General	Preliminary	Defined	Defined	Defined
Technology selection	General	Preliminary	Defined	Defined	Defined
Site location	General	Preliminary	Defined	Defined	Defined
Contracting model	General	General	Preliminary	Defined	Defined
Change and escalation strategies	None	Preliminary	Defined	Defined	Defined
Integrated project plan	None	Preliminary	Defined	Defined	Defined

Table 1:Programme maturity estimate classification.

B. Technical and Design Maturity:

FOAK fusion projects, which involve early-stage technologies with low Technology Readiness Levels (TRLs), face significant integration challenges due to the complex nature of plasma physics [17] and its interaction with materials, structures etc.

During the conceptual design phase, it is anticipated that cost estimation would be beyond the Class 5 level due to a lack of detailed design and clarity on system integration. As we transition towards the end of detailed design phase the expectation would be to achieve a Class 3 estimate. This phase would involve cost estimation based on the completions of all basic engineering documents, as well as starting preliminary mechanical and structural drawings. This is broken down into further detail below in Table 2.

Estimate classification	Class 5	Class 4	Class 3	Class 2	Class 1
Block flow diagrams	Started / Preliminary	Preliminary / Complete	Complete	Complete	Complete
Plot plans		Started	Preliminary / Complete	Complete	Complete
Soils and hydrology		Preliminary	Complete	Complete	Complete
Materials selection		Preliminary	Preliminary / Complete	Complete	Complete
Process flow diagrams		Started / Preliminary	Preliminary / Complete	Complete	Complete
Utility flow diagrams		Started / Preliminary	Preliminary / Complete	Complete	Complete
Piping and instrumentation diagrams		Started	Preliminary / Complete	Complete	Complete
Heat and material balances		Started	Preliminary / Complete	Complete	Complete
Process equipment lists		Started / Preliminary	Preliminary / Complete	Complete	Complete
Utility equipment lists		Started / Preliminary	Preliminary / Complete	Complete	Complete
Electrical one-line diagrams		Started / Preliminary	Preliminary / Complete	Complete	Complete
Specifications and data sheets		Started	Preliminary / Complete	Complete	Complete
General arrangement diagrams		Started	Preliminary / Complete	Complete	Complete
Spare parts listings		Started / Preliminary	Started / Preliminary	Preliminary	Complete
Mechanical drawings		Started	Started	Preliminary	Preliminary / Complete
Electrical drawings		Started	Started	Preliminary	Preliminary / Complete
Instrument and control system drawings		Started	Started	Preliminary	Preliminary / Complete
Civils / structural / site drawings		Started	Started	Preliminary	Preliminary / Complete

Table 2: Technical and design maturity classification

C. Commercial Strategy Maturity

While the impact of commercial strategy cost uncertainties may not be as pronounced as the prior two sources, they remain a necessary aspect to assess. The commercial strategy encompasses critical elements related to project procurement, partnership arrangements, contractual terms etc. In the early stages of a FOAK fusion power plant project, the supply chain may be non-existent, underdeveloped, or lacking maturity. This poses challenges in accurately estimating the costs of components and materials, as reliable market data and pricing information may be limited. Large-scale FOAK projects often involve bespoke and/or long lead items, which are critical components or equipment requiring an extended lead time for manufacturing or delivery. The uncertainties associated with an immature supply chain can impact cost estimation and procurement planning. Table 3 defines the class requirements at each stage of the cost uncertainty estimate.

Estimate classification	Class 5	Class 4	Class 3	Class 2	Class 1
Procurement strategy	General	Preliminary	Defined	Defined	Defined
Procurement packaging strategy	None	Preliminary	Defined	Defined	Defined
Partnering arrangements	General	Preliminary	Defined	Defined	Defined
Terms and conditions	General	Preliminary	Defined	Defined	Defined
Incentivisation arrangements	General	Preliminary	Preliminary	Defined	Defined
Securities and guarantees	General	Preliminary	Defined	Defined	Defined

Table 3: Commercial strategy maturity classification

D. Estimate Underpinning

Cost estimation often relies on analogies and comparators to existing technologies. However, the inherent differences between fusion and other technologies introduce large uncertainties as analogous programmes for a fusion power plant are practically non-existent.

Consequently, when attempting to cost projects at the concept design phase it is assumed any estimates will have a substantial uncertainty range likely exceeding a "Class 5" uncertainty range. As the project progresses from initial stages, such as top-down costing, to more detailed phases like bottom-up costing, there is a notable reduction in uncertainties. This transition, marked by the development of a comprehensive cost estimate, represents a pivotal stage where uncertainties begin to take on a more distinct form. At this phase uncertainties can be methodically characterized and broken down into a greater level of granularity.

Table 4 provides an overview of estimate classifications of estimate underpinning characteristics, ranging from Class 5 with a very low level of project definition to Class 1 characterized by high project definition.

Estimate classification	Estimate underpinning
Class 5	• Very low level of project definition • High level benchmarks • Expert opinions
Class 4	• Low level of project definition • Parametric cost data • Reference projects
Class 3	• Reasonable level of project definition • Unit cost line items • Detailed take-offs / bills of quantities • Supply chain prices
Class 2	• Good level of project definition • Unit cost line items • Detailed take-offs / bills of quantities • Supply chain prices
Class 1	• High level of project definition • Unit cost line items • Actual design quantities Contracted supply chain prices

Table 4: Estimate underpinning maturity classification.

During the early conceptual design phase, high uncertainties are common due to various factors stated (see Figure 1). The absence of a detailed and mature schedule poses challenges in accurately estimating costs and timelines. Furthermore, the limited design and technical maturity of the fusion power plant at this stage introduces additional uncertainties related to the costs associated with developing and implementing novel technologies.

As the project progresses into the detailed design and construction phases, there is a gradual reduction in uncertainties. With the refinement of the design and the increasing technical maturity, there is a clearer understanding of the required components, materials, and construction processes. However, it is important to note that even during these phases, some level of uncertainty remains as unforeseen challenges may arise during construction or engineering design modifications.

As the project transitions towards plant operation, uncertainties are expected to decrease significantly. With a fully functional and operational fusion power plant, the project team gains experience, accumulates operational data, and can better estimate costs related to maintenance, fuel, and operational processes.

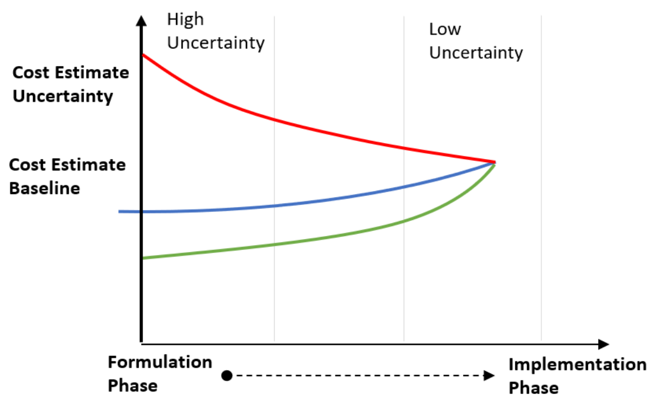

Figure 1: Typical evolution of uncertainties in programmes. The accuracy range is expected to reduce, while the base estimate typically increases [18].

III. BEST PRACTICE OF REPORTING/EVALUATING UNCERTAINTIES IN COST ESTIMATION

A standard best practice cost estimate is built by combining the base estimate, cost estimating uncertainties and the costed risk impact [5] as shown in Figure 2. For megaprojects like fusion power plants, it is then prudent to correct the final value for any residual optimism bias, often determined through processes such as reference class forecasting [19]. The base estimate involves determining the expected cost of designing, manufacturing, and integration of a component within the fusion power plant. This estimation is based on factors such as material costs, labor costs and engineering efforts. Risk refers to the potential negative impacts that can affect the project's cost estimate. These are conditions that might occur that lead to cost overruns, these risks can range from supply chain disruptions, manufacturing defects or other unforeseen events. Finally, uncertainties refer to the upper and lower cost range applied to the base estimate, they consider potential fluctuations and variations of cost due to a various source of uncertainty. Accounting for uncertainties is crucial to ensure that the cost estimate remains within a realistic range. It is important to note that cost estimates are subject to potential biases, such as optimism bias, which tend to underestimate costs. To address this, an optimism bias correction is applied to the anticipated final cost. This correction factor helps to counterbalance the inherent tendency towards underestimating costs and ensures a more realistic and conservative estimate.

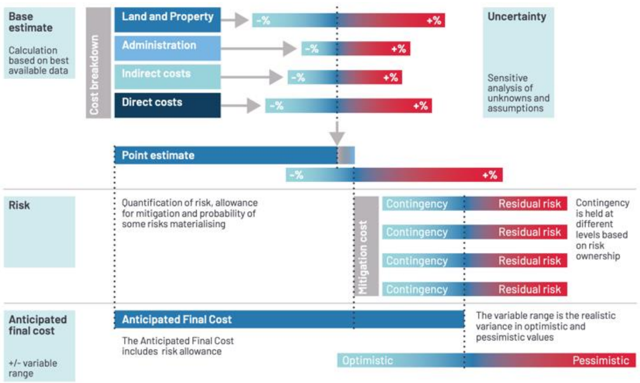

Figure 2: IPA cost estimating guidance best practice buildup of anticipated final cost estimate and confidence range [5].

IV. Application of Cost Uncertainties in the STEP Programme

As the STEP programme is completing its conceptual design phase, it is gaining the maturity to evaluate the impact of the uncertainties of the individual cost accounts onto the total programme costs. So far, the programme has been recording individual uncertainties without propagating them to the total costs and has even seen increases of cost uncertainty as the understanding of the design matured. As a result, there has not been sufficient confidence in the total programme estimate so far and uncertainties are partially expected to be larger than the range expected for Class 5 estimates. This is in line with lessons learned from other programmes (e.g. [20]), which find that "early-stage cost estimates are unreliable predictors of the eventual cost of megaprojects. This is valid across all nuclear technologies and large non-nuclear megaprojects."

Just like other fusion FOAK projects, STEP lacks benchmarking data due to its unique and innovative nature. Without comparable projects or historical data, it becomes challenging to estimate uncertainties based on industry norms or past performance. Uncertainties are often easier to estimate and propagate when supported by quantifiable data. As a result, while we have been able to identify ranges of uncertainties, it has been challenging to identify appropriate distribution functions. Consequently, sensitivity studies need to be carried out to understand the impact.

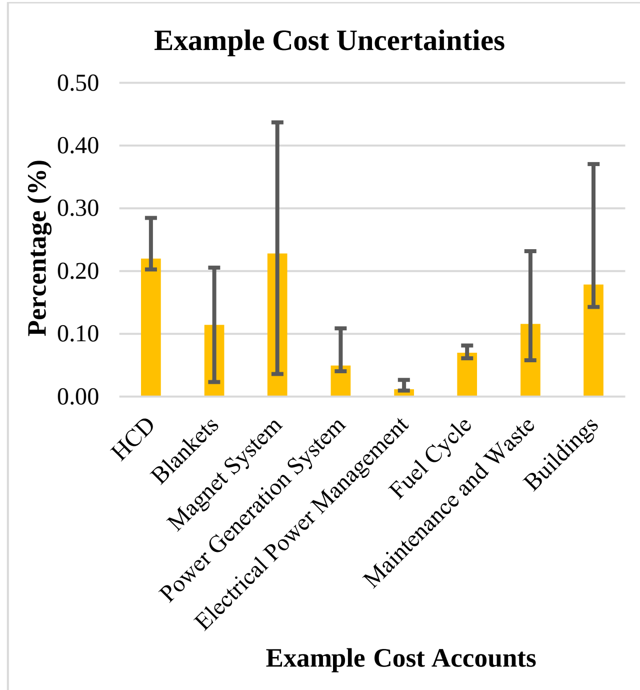

Figure 3: Example uncertainties of selected reactor equipment cost account.

Figure 3 presents examples cost account breakdown for the STEP project, with each account depicted by an error bar that signifies the associated uncertainty range. These cost accounts encompass various crucial aspects of the fusion project, and the variations in the size of the error bars reflect the diverse levels of uncertainty attributed to each component.

The uncertainty ranges vary quite drastically across the different accounts. Magnets on STEP represent a focal point of significant cost uncertainties. These uncertainties stem from a complex interplay of factors, making magnets a challenging and volatile cost component. Firstly, the technical complexity of fusion magnets is a primary driver. The engineering of the magnetic coils demands cutting-edge materials and manufacturing techniques, often with limited precedents. The resulting technological innovation introduces inherent uncertainties in design, performance, and, consequently, cost. Moreover, the uncertainty in material costs further exacerbates the issue.

Likewise, the Blanket has high uncertainties due to their low TRL. In the early stages of fusion development, these technologies are less mature and have limited operational experience, making it challenging to accurately estimate their costs.

The buildings account exhibits a significant uncertainty range this is as there is a lack of dedicated fusion-specific regulations that provide clear guidance and standards for the construction and operation of fusion facilities. This regulatory gap means that fusion projects like STEP must navigate their building processes with less-established frameworks tailored to their specific needs. This creates larger than usual cost uncertainties in the building account.

Unlike the Magnets system and Blanket account, the Electrical Power area has a much smaller uncertainty range. Compared to cutting-edge fusion technologies like magnets or plasma confinement systems, electrical power systems generally involve lower technical complexity. Electrical components and materials, such as transformers, generators, and cables, are typically part of mature markets with stable pricing. Market fluctuations are less pronounced compared to specialised materials used in fusion magnets, contributing to reduced uncertainty in material costs.

As the STEP programme advances through its conceptual design phase, it is gaining the ability to evaluate the influence of uncertainties on individual cost accounts. This variation in uncertainty ranges underscores the need for tailored cost management approaches for different fusion project components.

V. Conclusion

While multiple efforts have been made in the past to evaluate the costs of prototype/demonstrator/commercial fusion power plants, previous work has not been evaluating or reporting on the uncertainties in these cost estimates. As fusion power plant programmes mature, it is essential to evaluate and communicate the accuracy range of their corresponding cost estimates and understand how they are expected to reduce over time.

It is best practice cost modelling to evaluate the base costs, corresponding uncertainties, risks and apply optimism bias corrections. Sources for cost uncertainties include, the technical and design maturity, the programme maturity, the status of the commercial strategy as well as the accuracy of the underpinning estimate. All of these are expected to decrease over time, as the overall work on the different aspects progresses.

The STEP programme is applying best practice cost estimating methods including the evaluation of uncertainties. Throughout its conceptual design phase, it has experienced cost uncertainties increasing, as more was understood about the design. However, due to the still highly uncertain nature of the costs in following its end of the conceptual design phase, it is difficult to determine the appropriate distributions of uncertainties making it difficult to determine corresponding P80 or P90 values. Therefore, currently only ranges are being reported.

Due to the large uncertainties, the STEP programme currently does not report total programme costs but is using differential costing to support the decision-making process for design decisions to optimize the cost of the STEP prototype power plant, while it is building more confidence in its total programme cost model. Going forward, the cost uncertainties are expected to decrease as the programme, design and commercial strategy mature.

To deliver cost estimates that assure confidence of investors and other stakeholders, it is essential for the fusion community to follow best practice cost estimation techniques including evaluation and reporting of uncertainties.

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Nousheen Nawal (Fellow, IEEE; Member IChemE) has received her master's degree in advanced chemical engineering from the University of Birmingham. She began working for UKAEA, Culham Science Centre, Abingdon, U.K., in 2021 as a Graduate Cost Engineer, primarily working on costing for the spherical tokamak for energy production (STEP) programme.

Hanni Lux (Member, IEEE; CPhys, IoP) has received a diploma degree in physics from the University of Heidelberg, Germany in 2007 and a PhD in theoretical astrophysics from the University of Zurich, Switzerland in 2010.

She currently leads the cost modelling team of the STEP programme at UK Atomic Energy Authority (UKAEA), United Kingdom. She joined UKAEA in 2013 and has held various roles covering fusion power plant integration and cost aspects. Prior to joining UKAEA she has held a postdoc position in theoretical astrophysics at the University of Nottingham. Dr Lux holds a chartership with the Institute of Physics and is a member of IEEE.

Rhian Chapman (Member, IoP) received her Master's degree in Astrophysics from Cardiff University in 2005 and worked within the defence electronics industry before moving to an engineering/transport consultancy. She completed a PhD in Planetary Science in 2018 and joined UKAEA's STEP programme in 2021.

James R. Cowan (Member, APM and Ch.PP), received his degree in Materials Science and Engineering from the University of Birmingham, UK, in 1994 and his Ph.D from the same institution in 1998.

After early years working in the civil nuclear power industry, he moved to the UK Ministry of Defense where he held senior positions leading major programmes. He joined UKAEA as STEP Director Programme Development in July 2023.