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1 Abstract

Fusion power could be one of a few sustainable options in a portfolio required to replace fossil fuels as the world's primary energy source. The attractive properties of fusion combined with the imperative to address climate change has resulted in a burgeoning interest in the field with a dramatic growth in privately-funded fusion ventures in recent years. Historically, fusion has been developed by governments globally, including through ITER, the largest scientific collaborative project ever undertaken. The result is that the majority of people working in fusion today as well as most of the intellectual property reside within the public sector. However, there is equally a recognition that the private sector plays a vital role in delivering large-scale infrastructure projects, especially at the pace and agility required in the case of fusion and because it is the private sector that ultimately will deliver a fleet of fusion plants. Therefore, many countries are increasingly pursuing variants of public-private partnerships in the delivery of fusion. In this paper we provide the perspective of expedient delivery of fusion through public-private partnership as presently intended in the UK fusion programme.

2 Context and fusion's technical challenges

A fusion power plant requires many diverse interconnected systems and many different science, technology and engineering challenges to be met simultaneously. The particular challenges depend on the technical approach being taken, of which there is a considerable range, but here we focus primarily on the approach that has had the majority of global investment and attention to date, viz. the magnetically-confined plasma via tokamak-based approaches using deuterium-tritium fuel. The largest single tokamak programme, ITER[1] , and the coordinated European effort designing its successor, DEMO[2,3,4] , have adopted an integrated approach from the outset; advances are needed in individual areas but only bring fusion energy closer if the other challenges are resolved in harmony. An holistic systems engineering approach will be needed, from the plasma to the turbines, via the blanket – a thermodynamically-efficient neutron-to-heat convertor made from materials resilient to neutron damage. All the components must be buildable, highly reliable, and maintainable, mostly robotically. The plant must also be acceptable to stakeholders[5] and regulators, and be affordable

More specifically, integrated tokamak fusion powerplants must simultaneously combine: (1) the creation and sustainment of a controlled burning plasma over long timescales with fusion-born alpha-particles dominating the plasma heating; (2) the controlled exhaust of heat and helium "ash" from the burning plasma core; (3) materials for a) the tokamak structures which have to sustain, for many years, large forces and pressures at high temperatures in the presence of high magnetic fields and exceptionally intense neutron fluxes, without generating unmanageable volumes of radioactive waste[1], and b) functional roles requiring resilient to neutron and gamma irradiation, e.g. magnets, electrical and thermal insulators, tritium permeation barriers, diagnostic windows and breeding (e.g. lithium-containing ceramics); (4) components using these materials, notably the power-conversion, breeding and shielding blanket and plasma-facing components, which can survive in the demanding

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[1] Whilst the volumes may be large, there will not be high-level radioactive waste from fusion

conditions within a fusion reactor; (5) the requisite high availability and efficiency of the machine and its systems to produce a viable levelized cost of electricity; and (6) the ability to breed and handle tritium fuel as well as detritiate components periodically and at end-of-life to minimise tritiated waste. Critical developments are needed in essentially all of these areas. These and other constituent parts – such as the high field magnets, fuelling, heating and current-drive systems, plasma and plant control systems, buildings and the systems to convert fusion power to electricity with very high efficiency – must be brought together in an integrated multi-disciplinary design satisfying regulation and safety requirements. Fusion is different from most other technologies in that a technology validation in a representative environment is only possible in a complete device and probably complete plant, and the cost and timescale of each step means that a succession of small-increment full physical prototypes is unrealistic. Making large steps leads to two additional challenges: (7) development of extensive reliable theory-based models and an advanced computing programme for optimisation and then robust, low uncertainty predictions of the plasma and materials performance; and (8) comprehensive in-silico design, digital prototypes, and finally models of components and systems to support convincing qualification of components. Solutions to the last challenge in particular can have much wider application to large scale industrial activities where large steps can reduce development time and cost. Advanced digital design and simulation capabilities in particular are needed in multiple industrial areas, and fusion can be thought of as an ‘advanced use case’ driving development of techniques and methodologies with much wider applicability.

3 Key issues in the commercialisation of fusion energy

There are multiple pathways to delivering fusion power. In the interests of simplicity, we will characterise these pathways as “Schedule-driven” and “Evidence-driven”, noting that there are many more nuanced approaches between. The ‘Schedule-driven’ pathway aims to produce a fusion prototype powerplant that produces net electricity as quickly as possible within the bounds of available funding, regulatory compliance and readiness of feasible technology (which may not yet be optimal). This pathway can consider prototypes with low machine availability and reliability, higher technical risk, higher volumes of irradiated waste, uneconomical cost of electricity during early operation and short machine lifetime. The intention is to demonstrate technical viability of powerplants at prototype level which it is hoped will build early momentum in the industry and could lead to earlier market adoption, in particular through focusing development effort more clearly and driving innovation through some competitive pressure. Such accelerated approaches may leave significant developments needed afterwards to arrive at deployable plants, and that needs early consideration in parallel. In contrast, the ‘Evidence-driven’ pathway waits for extensive evidence to resolve further technical challenges before embarking upon the construction of a prototype to reduce the uncertainty (and thus financial risk) – such as developing low activation materials to minimise waste, or testing macroscopic components under prototypical neutron loads. Whilst this reduces the investment risk for the prototype and likely improves lifetime and availability of the prototype’s operation, it might result in slower adoption of fusion power into the market and requires considerable up-front capital to build expensive testing facilities.

When faced with the level of uncertainty, technical challenge and multi-faceted risk to delivering fusion power, it is difficult to be definitive about when fusion power can be delivered. That said, there are a number of aspirations committed in different roadmaps. In the ‘Schedule-driven’ approach, 93% of private fusion companies are aiming to deliver a fusion prototype device during the 2030s[6]. Still adopting the principles of the ‘Schedule-driven’ approach, but with an increased intention to await evidence, the most ambitious public programmes are the UK fusion strategy[7], the US National Academies strategy[8] (which stimulated a White House decadal vision for fusion[9] and subsequent public-private partnership programme[10]) and the Chinese Fusion Engineering Test Reactor[11], all of which aim for prototype full plants commencing operations around 2040. The most advanced of the more 'Evidence-driven' approaches is the EUROfusion roadmap to deliver a Demonstration fusion power plant shortly after 2050[12], presently linked to the ITER schedule, but even this is still ambitious and high risk by many conventional infrastructure project standards.

Estimates of the time for both 'schedule-driven' and 'evidence-driven' pathways to a first protype fusion power plant range considerably - from 2030's to 2050's. Further, as first prototypes they are likely to be low duty cycle, low availability, low electrical power and high cost of electricity, and thus probably not commercially viable. This ought not be surprising, as rarely do new concepts enter the energy market and become cost competitive from the prototype stage. The penetration of fusion into the market is almost impossible to predict when looking beyond the 2040 timescale, but one could explore whether it is possible to make penetration as quickly as other comparable large technologies, such as early adoption of oil & gas, or early adoption of conventional nuclear fission powerplants. If it were valid to use such previous growth rates as a guide, then for one example based on a historical cost-estimates of a fusion plant and specific assumptions about the future energy market, fusion could provide 10% of global energy demand by 2100 – equivalent to supplying all of Europe - or as much as 40% if capital costs were 30% cheaper, though as low as 1% if costs were 30% more expensive. While this is only a preliminary study with a range of assumptions, it does indicate the importance of capital costs in determining market penetration[13,14,15], if fusion deployment is not driven significantly by strategic considerations.

Despite the uncertainty, it is clear that under all pathways and historic precedence for market penetration, it is unlikely that fusion will make any significant contribution to global energy supply before 2050, though has the potential to play an increasingly large role in sustaining energy provision during the second half of the century and especially beyond, when the lifetimes of some of the intermediate strategies will be exhausted and when global energy demand will have risen well beyond 2050 estimated demand.

The electricity produced by a fusion plant must be acceptably affordable, even if there might be national strategic drivers. The abundancy and low-cost required to source fuel for fusion reactors (principally deuterium and lithium to breed tritium) mean that the Levelized Cost of Electricity (LCOE) may well be dominated by the construction cost of the plant[16] (similar to 'conventional' nuclear fission powerplants), although this depends on the operational costs which vary between concepts. Naturally, the economic performance of future fusion plants is uncertain given their inherent technological and scientific challenges, and estimates of the LCOE for fusion plants vary. General expressions for the LCOE of a fusion plant have been provided by, for example, the PROCESS code[17,18,19] which show that dominant contributions are in operations and maintenance, capital, and replacement costs. Principle mechanisms that might vary capital cost are the size of the plant and the modularity of the plant core, though the capital cost of a fusion reactor is presently hard to predict. On the size, larger plants and/or more plant cores may produce more energy but at increased capital cost. Major contributors to the operational cost are the availability, cost of consumable components and the overall conversion efficiency of the plant. The efficiency is largely dominated by specific technical details of the core fusion system and is not discussed here, however availability is impacted by a number of general considerations. Concerning modularity, it has been seen that repeated cores has been a way to drive down cost of megaprojects[20]. However, it is likely that there will be a minimum unit size in fusion for commercial viability[21,22] due to the large recirculating power requirements of all fusion devices. That said, tokamaks can benefit from modularity through symmetry and self-similarity of parts of the powerplant leading to significant repeatability in the manufacturing and assembly process.

The high energy density of D-T fusion leads to an inevitably high flux of energetic neutrons incident on machine components and tritium breeding systems, higher for concepts with higher power density. These conditions will result in activation and damage to materials and thereby components which will require a schedule of planned maintenance. To maximise the availability of the plant, this planned maintenance must be carried out as efficiently as possible, and the components must be designed to have as long a life as possible as well as designed for rapid replacement. The hazardous environment (resulting from activation, the presence of tritium, and other hazards) however require this maintenance to be conducted without exposure of humans. This necessitates remotely operated maintenance activities, but also an approach that enables more optimal offline maintenance of highly activated components whilst new components are rapidly shipped in to enable power operations. Novel materials and efficient maintenance activities are likely to be required to withstand the fusion environment and ensure the plant is able to operate for a sufficient period to depreciate fully the capital costs and offer a sufficiently attractive economic or practical proposition to energy providers.

Critical to the economic performance of a fusion plant will be the proportionate amount of time spent producing energy, known as the availability of the plant. For current 'baseload' energy supply this number is typically in the region of 80% - 90% [23] and fusion power plants must approach if not compete with these levels if they are to effectively penetrate a free energy market in the future (though some nations might be ready to consider higher costs for strategic reasons) . It is controlled mainly by the lifetime of individual components and the time to replace them (planned maintenance), but also by unplanned stoppages of the plant core, and the time required to bring the system back online. Such unplanned stoppages may include off-normal events in the core fusion system which require shutdown and restart, or failures in external sub-systems of the plant which will be common to all fusion approaches (e.g. the tritium storage and reprocessing plant).

The UK has a strong heritage in developing fusion power, having operated JET[24] for forty years, constructing the new MAST Upgrade device[25,26] and a more recent expansion into materials[27], robotics[28], fusion technology[29], tritium[30], manufacturing and computing[31]. Building on this broad and extensive fusion research and technology programme, UKAEA is now embarking on the design of a prototype UK fusion powerplant - the Spherical Tokamak for Energy Production[32] - known as STEP. An initial concept design phase for STEP began in 2019 with the ultimate aim of constructing a prototype powerplant by around 2040 that is capable of demonstrating the key outcomes of later commercial plants, including: producing net electricity; breeding sufficient tritium fuel to sustain operations; and proving a viable maintenance philosophy.

4 Regulation

Another aspect that will critically affect the readiness of industry and investors alike to participate in the delivery of fusion is the certainty of how fusion will be regulated and licensed. To this end, the UK government have stated that they "believe that the regulatory framework for fusion should be proportionate and appropriate to the hazards associated with fusion energy facilities" and as a result have brought forward primary legislation to establish such a framework[33]. In the case of the UK this means that fusion will continue to be regulated in the UK by the Health and Safety Executive and environmental regulators, rather than by the Office for Nuclear Regulation. Following this decision, the US Nuclear Regulatory Commission also announced that in the US fusion would not be regulated in the same way as fission powerplants[34]. Regulation requirements can reach back into the technical design choices in significant ways.

5 The UK approach to public-private partnerships in fusion

The UK has a clear fusion strategy published by the government in 2021[35] to build a prototype fusion powerplant which delivers net electricity, and to establish an industrial base capable of delivering fusion powerplants globally. This intrinsically involves a range of roles for public and private organisations, separately and in partnership. We indicate a few of these here. These roles will be defined and evolve as the field progresses (for example the approaches for prototypes and fleets may be different due to the likely difference in risk appetite of investors and stakeholders).

There are a few types of public and private actors in the UK, and the situation is similar in other nations. Public actors include (i) government departments, (ii) public sector research organisations (notably UKAEA, but others also play a role, for example organisations with powerful specialist digital, technology, standards and safety capabilities applicable to various fields as well as fusion), (iii) universities, (iv) technical training organisations; and now (v) fusion delivery organisations (notably UKIFS in the UK, see below). Likewise private organisations cover a spectrum, including (i) organisations aiming to provide complete devices and/or full plants (presently mainly prototypes) around a specific concept; (ii) companies solely focused on providing fusion technology solutions (often for a range of concepts); (iii) technology, manufacturing and digital companies expanding their portfolio into fusion to provide bespoke or common fusion technologies and capabilities. This last sector in particular provides a direct avenue for near-term cross-benefits between fusion and adjacent fields, an aspect that may be critical for some stakeholders given the long delay before the return on investment from the energy market, and thus may be a critical factor in public-private partnerships.

There are already a number of different approaches to public-private partnerships in fusion which can be characterised by whether the relationship is led from the public sector, the private-sector, or is a joint approach (as distinct from the strict commercial definition of a ‘Joint Venture’). Indeed, of course the arrangements for each venture are bespoke and can appear anywhere in this sliding-scale, though for simplicity-sake, we give likely traits of different approaches in Table 1.

Dominant partner	**Public**	**Joint**	**Private**
Foreground IP owner	Public	Could be vested in either entity or jointly owned	Private
Nature of procurement process	Public	Most likely mixed approach, eg: • Public procurement of private partners, then private procurement of supply chain • Collaboration agreement	Private
Role of industry	Suppliers to public entity	Collaborative strategic partnership arrangements	Private company leads the endeavour and chooses public partners
Example	ITER domestic agencies, eg F4E[36]	Italian DTT[37], STEP (see section 5.1)	US Milestone-based Fusion Development Program[38],[39],[40]

Table 1: nature of different approaches to public-private partnerships

5.1 The public-private partnership approach of STEP

STEP’s objectives are to deliver a prototype fusion plant and demonstrate that fusion energy can become commercially viable. In doing so, the programme will stimulate a UK fusion supply chain which can benefit from the future export of fusion technologies.

STEP will be delivered by UK Industrial Fusion Solutions (UKIFS)[41], a new company-limited-by-shares, which is being set up initially as a subsidiary of UKAEA. UKIFS is being established as a delivery body for a multi-£Bn mega-project, whereas UKAEA is a national organisation specialising in science, innovation and technology. The proposed approach is that UKIFS will contract with two industry partners (Whole Plant Partners – which could be single organisations or more probably consortia of organisations), in addition to UKAEA as the fusion partner, to secure access to the capabilities that UKIFS needs to deliver the programme. This is intended to be a long-term collaborative partnering relationship with the industrial partners, utilising successive work packages to contract for people, tasks and services under the contractual arrangements. The long-term nature of the contracts requires that partners must be strategically and behaviourally aligned as well as providing critical capabilities. The novelty, scale and complexity of the STEP Programme means that UKIFS must retain the overall delivery risk. The preferred commercial approach will allow appropriate risk to be delegated to industry dependent on the nature of each work package and progressively as the design matures. The integration of capabilities through collaborative working and appropriate leadership is shown in Figure 2. Due to the diverse and complex nature of fusion powerplants, the primary engineering partner will have to use a broad range of Tier 2 designers, manufacturers and suppliers as well.

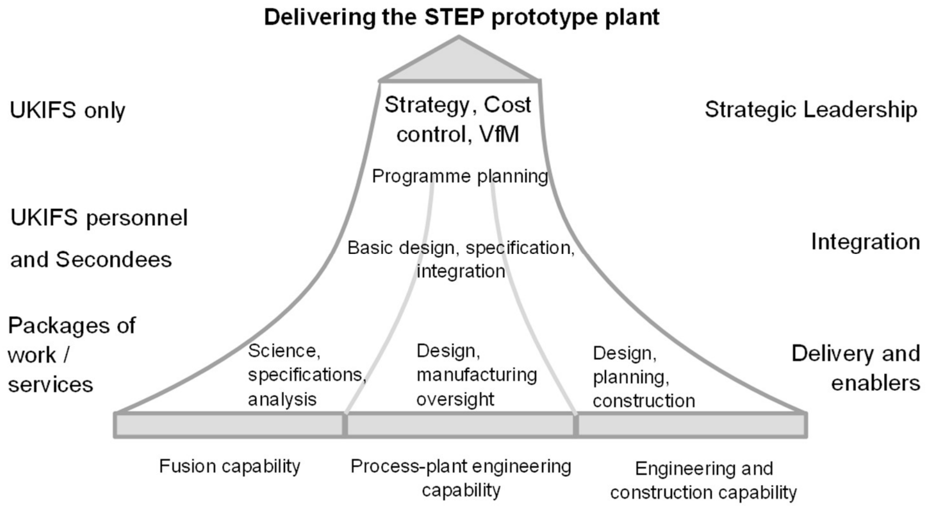

Figure 2: integration of capability to deliver the programme

5.2 Other public-private fusion programmes

Beyond 'concept-driven' programmes, such as the US Milestone-based public-private partnership programme, or the STEP programme, other notable public-private initiatives are more 'capability-driven', which is to say that a partnership between public and private entities has been established to develop capability which is concept agnostic. Often this is intended to transfer technology and knowledge from the public-sector research community into the industrial sector, such as the Fusion Industry Innovation Forum[42] in the EU, or more recent schemes have been established to 'challenge' industry to solve some of the problems faced in delivering fusion for which there are no substantiated solutions, such as the Fusion Industry Programme[43] in the UK. These could be important preparation for the stages after the early prototypes.

5.3 The benefits of 'clustering' in the fusion ecosystem

A final form of relationship between public and private entities is the colocation of these different organisations in the same physical 'clusters'. Clusters of innovation - described by

Porter[44] as *"geographic concentrations of interconnected companies and institutions in a particular field"* – have been studied extensively[45], and show considerable benefits in advancing innovation. Silicon Valley, centred around San Jose, is a much-vaunted example of a highly-successful cluster, and many attempts have been made, with varying degrees of success, to replicate this cluster effect in other fields and in other locations. Although the effects of the sharp rise in remote working caused by the global pandemic are likely to have some influence on 'clusters', it seems likely that clusters will retain a potent connection with progress in innovation.

6 Evolution in the roles of public and private sectors

The UK's experience in developing the largest offshore wind provision in Europe has been that it has proved essential to involve existing energy operators (including utilities, transmission network operators and energy provision companies). Indeed, in 2020, 73% of the operational windfarm capacity was owned by conventional utilities and oil and gas companies[46]. This engagement of companies involved in delivering and operating energy infrastructure and their supply chains is integral to the UK's strategy for delivery of fusion too. McKinsey's recently analysed the role for oil and gas majors in leading low-carbon energy delivery, citing "their global scale, the risk appetite of their investors, their large balance sheets and cash positions, and their long-standing relationships with energy customers and stakeholders"[47]. Indeed, oil and gas companies have already begun investing in fusion companies[48]. Beyond energy companies, the fusion sector is also seeing notable interest from other sectors where there is interest in the cogeneration capability or adjacent benefits of fusion technology, for instance recent investments from major automotive companies[49],[50].

At the present state of maturity in the fusion sector – namely that there are major technical risks remaining and as yet limited confidence whether these challenges are surmountable – it is natural that the public sector is needed to undertake projects on a multi-£Bn powerplant-scale, such as ITER. However, if technical challenges can be overcome and confidence increases, then it is likely that private-sector companies will adopt leadership beyond the prototype stage. Even in this scenario, there is likely to be an enduring need for public investment, for instance in research and development of next-generation components or even full powerplants, and an enduring need for wider government support including: creating a stable and supportive energy policy that gives confidence to investors; ensuring an enabling regulatory framework; creating clear and efficient permissioning systems for the site; and agreeing financial models such as the Regulated Asset Base or Contracts For Difference mechanisms that have been extensively used in the UK[51].

At present there are more than forty start-up venture-backed fusion companies and the precedent across the technology sector[52,53] suggests the vast majority of these will not transition to be integrated plant vendors. Currently the range of technical approaches being taken by the companies is notably wide, further evidence that there is some way to go before the field of fusion reaches technical maturity. As the sector matures, it is likely that there will be consolidation in fusion to far fewer tier one (i.e. whole-plant) vendors, both because of the scale of capital needed to deliver fusion powerplant, and also as technical maturation results in fewer technical approaches being followed. Even in the renewable energy sector – where capital outlays have been historically much lower than the likely overnight costs of fusion but are now increasing as the scale of projects grows to meet low-carbon energy provision targets – the market is witnessing a trend towards mid-scale consolidation as firms seek to reach critical mass for large projects[54]. The public sector in fusion will need to navigate ever closer relationships with an evolving cohort of private sector companies with some skill – collaborating widely but acknowledging the likely consolidation in the private sector.

7 Development of the fusion supply chain and required skilled people

No matter whether fusion is delivered by a public-private partnership, or by another mechanism, if fusion energy is to be delivered it will require major stimulus of supply chain capability and development of skilled people, both of which are presently rate-limiting for the ITER project. A 2017 study[55] provides evidence of market spillovers on fusion projects (ITER and KSTAR), indicating a 19.1% average increase in sales, creation of new jobs, and that 62% of collaborating enterprises extend their businesses to other relevant technological fields. A later 2021 European Commission study[56] showed that the ITER project has had a large positive impact on EU suppliers in technology and industrial sectors. This year, the Fusion Industry Association reported that private fusion companies spent $500M in their supply chains[57], with this set to grow to £7Bn p.a.

Fusion powerplants will require the development of many industrial capabilities which are either nascent or non-existent today. This includes, inter alia, advanced magnet technology and materials (notably suitable high temperature superconductors), the enrichment of lithium for tritium breeding, the fabrication at scale of oxide-dispersion strengthened and/or other advanced alloys, advanced manufacturing with many exotic materials required in the exacting combinatorial-load environment of a fusion plant, extraction of, and separation of, tritium at the scale and pace needed for self-sufficient tritium production and the at-scale development of heating and current drive systems for plasma production, sustainment and control.

Finally, it is also worth noting that successful delivery of fusion power will be dependent on a supply of highly-trained capable scientists, technologists, engineers, mathematicians and modellers. Therefore a concerted sector-wide training programme is required at all levels, from apprentices, to graduates, to post-graduate students and post-doctoral researchers.

8 Conclusions

Fusion offers enormous potential as part of a sustainable portfolio of low-carbon energy sources for the future. Recent technical developments, coupled with the increased cognisance of the imperative to tackle climate change, have resulted in marked increases in both public and private investment in fusion. However, the expedient delivery of fusion powerplants will require a greater cooperation between public entities, where much of the fusion knowledge and IP currently resides, and private sector entities with the agility and experience in delivering products to market. This will also require the coordination of a broad, nascent supply chain with small-to-medium sized enterprises and, most probably, major multinational corporations. Such partnerships will represent a new paradigm for the fusion sector. The UK has developed a fusion strategy precisely to foster such a paradigm and made a number of interventions in recent years to establish these public-private partnerships in order to realise the potential of fusion energy.

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