FUSION ENERGY: A GLOBAL EFFORT– A UK OPPORTUNITY.

Institution of MECHANICAL ENGINEERS

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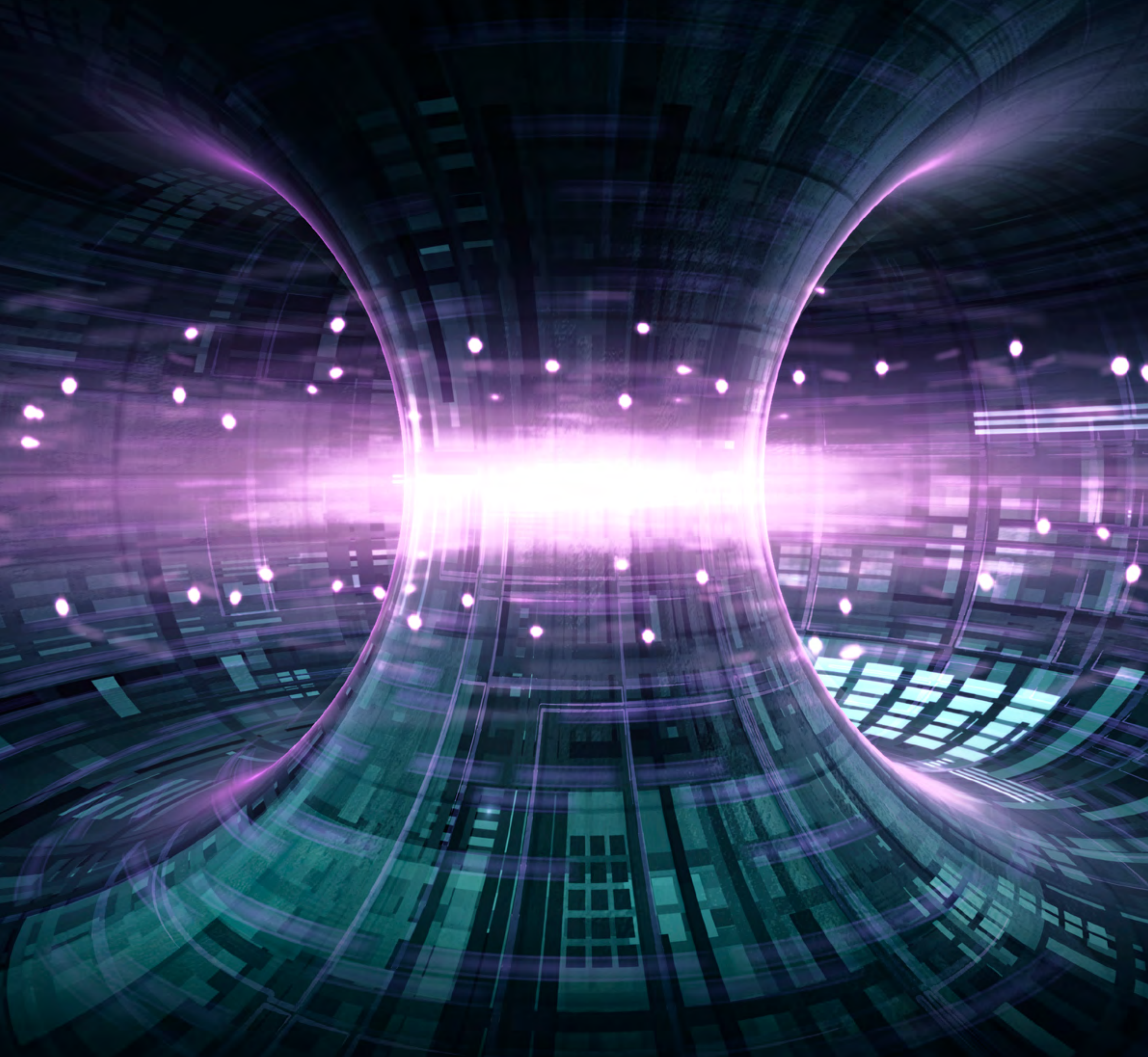

Improving the world through engineering

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Fusion offers the potential for abundant low-carbon energy with a small environmental footprint. It is an important technology option for delivering a sustainable global energy system and the UK is well-placed to benefit from being a leader in the sector.

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Head of Engineering Policy
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The IMechE's Engineering Policy Unit was commissioned by Assytem to produce a report into the current status and future prospects of fusion energy, with a particular focus on the UK. Whilst keeping to the brief provided by the sponsor, the content and conclusions of this report are entirely those of the IMechE research team.

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The IMechE were early investors in Tokamak Energy through their Stephenson Fund and hold a small number of shares in the company.

About Assystem

At Assystem our global engineering footprint is focused on the energy transition projects that will reduce the impact of climate change. We are an engineering partner to the governments, investors, owners, and OEMs developing today's innovative low-carbon technologies, such as fusion energy

Fusion offers the potential for limitless power using a sustainable fuel source and leaves no harmful legacy to the environment. Today, fusion is within reach as the major experiments have successfully stimulated a private fusion sector. The realisation of fusion would meet global energy demand for low-carbon power. Fusion energy would be a stable partner in energy systems, as well as a source for hydrogen production and other new fuels for industry and transportation. Assystem is a committed partner in the development of low-carbon technologies, which is why we have commissioned this report to highlight the current opportunity for progress in the commercialisation of fusion energy.

A concise Summary for Policymakers is available alongside this report on the IMechE website: https://imeche.org/policy-and-press/reports

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Foreword

Two of the core objectives of the Institution of Mechanical Engineers are to develop engineers and to maximise their positive contribution to society. The fusion industry embodies both.

The UK's fusion cluster, partnering with research centres around the world, is pushing the limits of possibility in the development of fusion reactors and associated enabling technology. For instance, many of our members have been working hard for years on the design and construction of the ITER project in the South of France to demonstrate the technical feasibility of fusion as an energy source.

The UK is also well-placed to be a leader in the sector. The R&D ecosystem built up over decades by the United Kingdom Atomic Energy Authority (UKAEA) is world-leading and has led to synergies with other sectors, including the space industry.

The increasing private investment in fusion means that it is no longer considered a far-off dream. Across Asia, Europe, and North America, entrepreneurs are beginning to speak with their wallets. Their aim is to accelerate the path to the day when we will see commercial fusion power plants. Challenges still exist, and it won't happen overnight, but more and more people are beginning to believe that this reality will come true. Engineering innovation will be key to making it happen at all stages of development and deployment.

The IMechE recognised the potential of fusion in 2015 when we invested in Tokamak Energy through our Stephenson fund, which is aimed at helping innovative companies bridge the gap from R&D to commercialisation. Government has also recognised that the sector is a strategic investment by providing funding for Tokamak Energy and the Spherical Tokamak for Energy Production (STEP).

So whilst there are still hurdles ahead, if the UK can crack this nut fusion could supply unlimited sustainable energy for humanity in the decades to come.

In publishing this high-level assessment of the fusion industry, with gratitude to Assystem for sponsorship, the IMechE hopes to promote engineering innovation and shine a light on what could be a key low-carbon technology of the future.

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Introduction

Globally and in the UK, interest in fusion energy is growing. The UK has a world class and expanding research centre at Culham in Oxfordshire and the International Thermonuclear Experimental Reactor (ITER) in the South of France is in the advanced stages of construction and assembly. Private sector activity has also accelerated, with over 15 fusion energy start-ups being created since 2009, including Tokamak Energy and First Light Fusion in the UK. The industry as a whole is gaining momentum.

The potential advantages of fusion have been known for a long time. A commercial fusion power plant would be a reliable energy source, with an essentially limitless supply of fuel, and would be low-carbon and produce much lower levels of radioactive waste than a fission plant. Essentially, commercial fusion would have many of the low-carbon advantages of nuclear fission and variable renewable energy technologies, with few of their downsides.

Fusion release large amounts of energy by combining, most commonly, isotopes of hydrogen. The first challenge for fusion technology is getting more useful energy out from the fusion reactions than is required to create the plasma in the first place. The next step will be to develop a machine that can achieve a stable and continuous plasma that can be used to produce useful electricity. Finally, there is the economic challenge. Electricity (and potentially also useful heat energy) must be economically and financially competitive with alternatives for fusion to find a place in the energy market. The challenges are real, but they have not deterred investment in fusion R&D because the potential rewards are huge.

Commercial fusion will not happen overnight. Numerous challenges need to be overcome before the world will see a fusion power plant selling electricity to the grid. This report examines the current state and future prospects of fusion. It sets out to explore:

- The potential role of fusion in future energy systems
- The steps that need to be taken to convert fusion reactors from scientific experiments to commercial power plants
- The cost drivers of fusion energy and the potential for cost reduction
- The financing options for different investment stages between fusion R&D and a commercial power plant
- The current capacity of the UK to support a fusion industry and the options for expansion
- The possible barriers to fusion energy and opportunities for the UK to lead in commercial deployment

A concise Summary for Policymakers is available alongside this report on the IMechE website: https://imeche.org/policy-and-press/reports


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Chapter 1
The role for fusion within future energy systems

This chapter includes:

- An analysis of what energy systems will look like in 2040–2060
- The role for fusion in complementing other low-carbon technologies
- A comparison of fusion with other dispatchable electricity sources
- An explanation of how fusion can provide heat as well as electricity

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Electricity demand is likely to continue to grow beyond 2050 in the UK and globally, driven by deep decarbonisation and rising standards of those living in developing countries.

A long term requirement for low-carbon electricity and heat

Commercial fusion power has the potential to become reality from the 2040s onwards. The need for fusion power must therefore be evaluated according to the energy market 20 or 30 years in the future rather than that of today. This market is undergoing major change driven by greenhouse gas emissions reduction targets, which will both increase demand to replace oil and natural gas, and radically alter supply to replace current fossil fuels with low-carbon generation. The future market has been studied for different countries and for the world as a whole. While exact predictions are not possible, different scenarios can be considered. Examples of such modelling efforts include the International Energy Agency's (IEA) World Energy Model[1], the UK Government's Department for Business, Energy and Industrial Strategy's (BEIS) Global Calculator[2], and for the UK, the National Grid's Future Energy Scenarios (FES)[3].

Studies consistently predict that variable renewable energy – predominantly wind and solar power – will play a significant role in the energy future because of their already large and continuing reductions in cost. Power sources that will complement these variable renewables are however dependent on the policy environment. Under business-as-usual scenarios that fail to meet the climate change challenge, fossil fuel will continue to make a significant contribution to global electricity supply, heating and transportation[4,5]. Other zero-carbon supplies including fusion would struggle to compete with fossil fuels in such scenarios, but these scenarios are incompatible with preventing catastrophic levels of global warming. Nuclear fusion is therefore a technology for a Net Zero world.

Many developed countries are committed to massive reductions in greenhouse gas emissions by 2050 under the Paris Agreement. The UK also has an emissions target of Net Zero emissions by 2050[6]. Other countries/regions have or are developing similar targets, for example the EU aims for Net Zero by 2050[7] and China by 2060[8].

It is important to recognise that only a fraction of our current energy consumption is electricity (18% in the UK in 2019[9]), with residential heating, transportation, industrial processes and agriculture all being significant contributors. In scenarios targeting Net Zero, National Grid FES forecasts that electricity demand in Great Britain will increase by ~50–150% by 2050 up to ~550–750 terawatt-hours (TWh). This is primarily due to electrification of transport and de-carbonisation of domestic heating heating (be this through hydrogen production, electrification, or otherwise).

The UK represents only ~1.5% of global electricity demand[10]. Globally, the share of electricity in the energy mix is expected to rise from 19% to 30% by 2050[11], while overall energy growth of 50% is projected by 2050[12]. World electricity use may therefore more than double by 2050 with the largest share of this growth expected to be in wind and solar power.

Commercialisation of a new technology like fusion energy in the 2040s leaves little time for deployment in order to make a significant contribution to 2050 emissions reductions targets. Nevertheless, electricity demand is likely to continue to grow beyond 2050 in the UK and globally, driven by deep decarbonisation and rising standards of those living in developing countries. Continuing the 2% annual growth rate corresponds to potential additional demand of 1.6 gigawatts (GW) of electricity capacity per year in the UK, and of the order of 600 GW per year globally. The market for electricity is therefore very large with investment needs in excess of a trillion pounds. If in the medium term nuclear fusion can be shown to work and produce electricity and competitive prices, the domestic and international market for fusion plants could be very large.

The need for dispatchable power

Electricity generation from variable renewables is widely projected to increase dramatically until 2050[13] and, according to Bloomberg New Energy Finance[14], will dominate low-carbon electricity grids in countries with strong emission targets. This will be driven by reducing costs as much as policy factors. Variable renewables, primarily onshore and offshore wind, are projected to meet around two thirds of UK electricity demand by 2050[15]. Globally, renewables are generally forecast to contribute around 80% of new electricity between now and 2050[16]. Particularly striking are cases like the US, where rapid expansion of solar power is projected even in scenarios where overall emissions remain fairly stable[17], driven by subsidies and falling prices. BEIS have estimated 2040 levelised costs of electricity (LCOEs) for the UK for stand-alone offshore wind, onshore wind and large-scale solar of £40 per megawatt-hour (MWh), £44/MWh and £33/MWh respectively[18]. Current prices for solar power and onshore wind are even lower in the USA where the conditions for solar power can be much more favourable[19]. In each case there will be additional system costs (such as storage or additional capacity) to address the inherent intermittency of these renewables.

It should also be recognised that the available renewable resource is extremely large and, on a global level, significantly more than will be required. For the UK, it is now accepted that expansion in offshore wind will not be limited by resource constraints. However, global renewable resources are not evenly distributed, with different countries having different balances of offshore/onshore wind, solar, hydro etc., and some countries/regions having relatively low renewable resources[20]. The marginal cost of electricity does and will continue to vary between different countries[21].

This raises the question: Why pursue fusion energy at all?

The primary reason lies in the high system costs that arise as variable renewables reach very high levels of system penetration. High variable renewables shares leads to large weather-driven fluctuations in electricity supply which, when combined with natural fluctuations in power demand, leads to both large swings in electricity supply and prices, and challenges to the continuity of supply. Hence the need for back-up and storage that are at the heart of system costs.[22] System costs for variable renewables will be incurred due to the following factors:

- Generation may be a significant distance from the consumption, introducing connection and transmission costs.
- Variability in generating profile may force other suppliers off the system. Weather patterns are variable, and solar power additionally follows a cycle according to seasons and time of day.
- Requirement for backup generation or overcapacity to compensate for intermittency with large-scale, long-term energy storage.
- Managing power grid stability in the absence of conventional thermal power plants.

Such costs are often not included in the costs of renewables generation. System electricity cost can be significant offsetting some of the low-cost advantages of renewables[23]. Nevertheless, renewables are generally expected to be competitive, certainly against other low-carbon power sources such as new build nuclear power, new hydro or BECCS (Bio-energy with carbon capture and storage). System costs rise faster as renewable penetration approaches 100%, as very large amounts of complementary low-carbon supply, energy storage and/or system overcapacity, perhaps of order 30–40% in UK, will be required to guarantee that demand can be met[24]. For a UK electricity grid with 100% renewables, this could increase the cost of electricity provided by renewables by 75–150%. Similar conclusions have been reached elsewhere[25].

This points to extremely high incremental costs as the fraction of variable renewables approaches 100%. To put it another way, the relative system cost of adding the last ~30% of variable renewables is much larger than the cost of adding the first ~70%. Alternative sources for this additional supply could cost substantially greater than £40/MWh while still delivering the lowest overall costs.

Various academic studies have investigated the feasibility of achieving 100% renewables in different markets, reaching similar conclusions that costs can become very significant, curtailment can exceed 40% and highly interconnected power systems are required[26,27]. This is the more nuanced manifestation of the question: "What happens when the wind is not blowing, and the sun is not shining and this continues for days or weeks?"

It seems likely that energy systems containing ~30% low-carbon dispatchable supplies (reliable energy on demand) ie that is not solar or wind, have the potential to be lower cost than energy systems containing 100% variable renewables. Such dispatchable generators are present in deep decarbonisation studies for various nations (and even then, many of these studies do not achieve Net Zero)[28,29].

Addressing the need for low-carbon dispatchable power

Aside from nuclear fusion, the technologies identified below have the potential to fulfil the need for low-carbon dispatchable power:

- Various forms of **fossil fuel generation combined with carbon capture and storage (CCS)**. This has the disadvantage of producing non-trivial CO_2 emissions that make Net Zero difficult to achieve[30]. Such power plants may also have to be situated close to suitable geological storage sites for carbon dioxide and have the associated costs of capture, transportation and storage. Re-utilisation of the CO_2 has been proposed as a means of improving the economics, but the market for this is relatively small. A market of 50 million tonnes per year exists at present, which is 0.1% of global emissions[31]. While the market may rise if new uses are developed, and emissions may fall, a substantial disparity is likely to remain. The current market for CO_2 re-utilisation mostly comprises enhanced oil recovery, which can be anticipated to fall in line with decarbonisation.
- **Bio-energy with carbon capture and storage (BECCS).** This has the advantage of enabling potentially negative carbon dioxide emissions, with disadvantage of being costly compared with fossil fuel CCS and nuclear fission[32]. Additionally, the energy density from bio-energy is extremely low[33] and may often require arable land (for comparison, solar power can be placed in deserts), which leads to its own set of negative environmental impacts.
- **Nuclear fission.** This has neither of the disadvantages flagged for the above technologies and has comparable LCOE to fossil fuel CCS[34]. However, due to high profile nuclear accidents and long-lived (albeit low volume) waste, political and public perception constraints may limit its deployment. Specifically in the UK and other Western countries, high capital costs and lack of financing have held back deployment, though these are not problems inherent in the technology.

Estimates of the future energy costs of CCS technologies[35], and nuclear fission[36] show they are higher than future variable renewables costs[37] (excluding system costs). This is projected to remain the case beyond 2040, with gas CCS and nuclear projected to be at least twice the cost of variable renewables and BECCS projected to be more expensive still[38].

Given the life cycle emissions associated with fossil fuel power, even when combined with CCS, and limits to sustainable biomass that can be used for BECCS, nuclear fission and fusion offer more sustainable ways of addressing the need for dispatchable power in the long term. Fission and fusion both have the advantage of high energy density, ie, they require relatively little land. They are also similar as both are characterised by high capital and low variable costs. For this reason, fusion and fission power may compete with each other.

In Western countries recent nuclear fission projects have experienced large cost overruns and new build LCOEs are currently significantly higher than those for variable renewables[39]. However with the right programme approach, fission is likely capable of producing electricity at prices within or below the target range identified above to contribute to a system that contains mostly variable renewables[40]. In Asia, substantially lower nuclear fission costs have been demonstrated than in the West through much reduced construction cost and build times, in large part enabled by standardisation and series build (as well as competitive state finance interest rates in some cases)[41]. Based on this analysis with a substantial programme of standard build it would be possible to reduce nuclear fission costs in the West to £60–70/MWh[42]. This fission energy cost provides the first target for nuclear fusion to be economically competitive.

Key advantages of fusion power are its almost limitless supply of fuel, its inherent safety and low radioactive footprint. This provides the potential to access markets that are unavailable to fission due to political concerns about safety and radioactive waste. This includes countries and/or regions with low public opinion of fission power or political opposition to construction of new fission plants (eg Germany, Italy, Japan, Taiwan, many US states[43]).

Here, the much lower production of radioactive waste by fusion reactors and very low potential for off-site radiological consequences are a potential pathway to public acceptance of fusion power in such regions. In the UK, creating new green-field sites for the construction of nuclear fusion reactors (potentially for the STEP engineering demonstrator[44]) may be easier than for fission reactors, for example, and hence may be complementary to construction of new fission reactors at existing nuclear licensed sites.

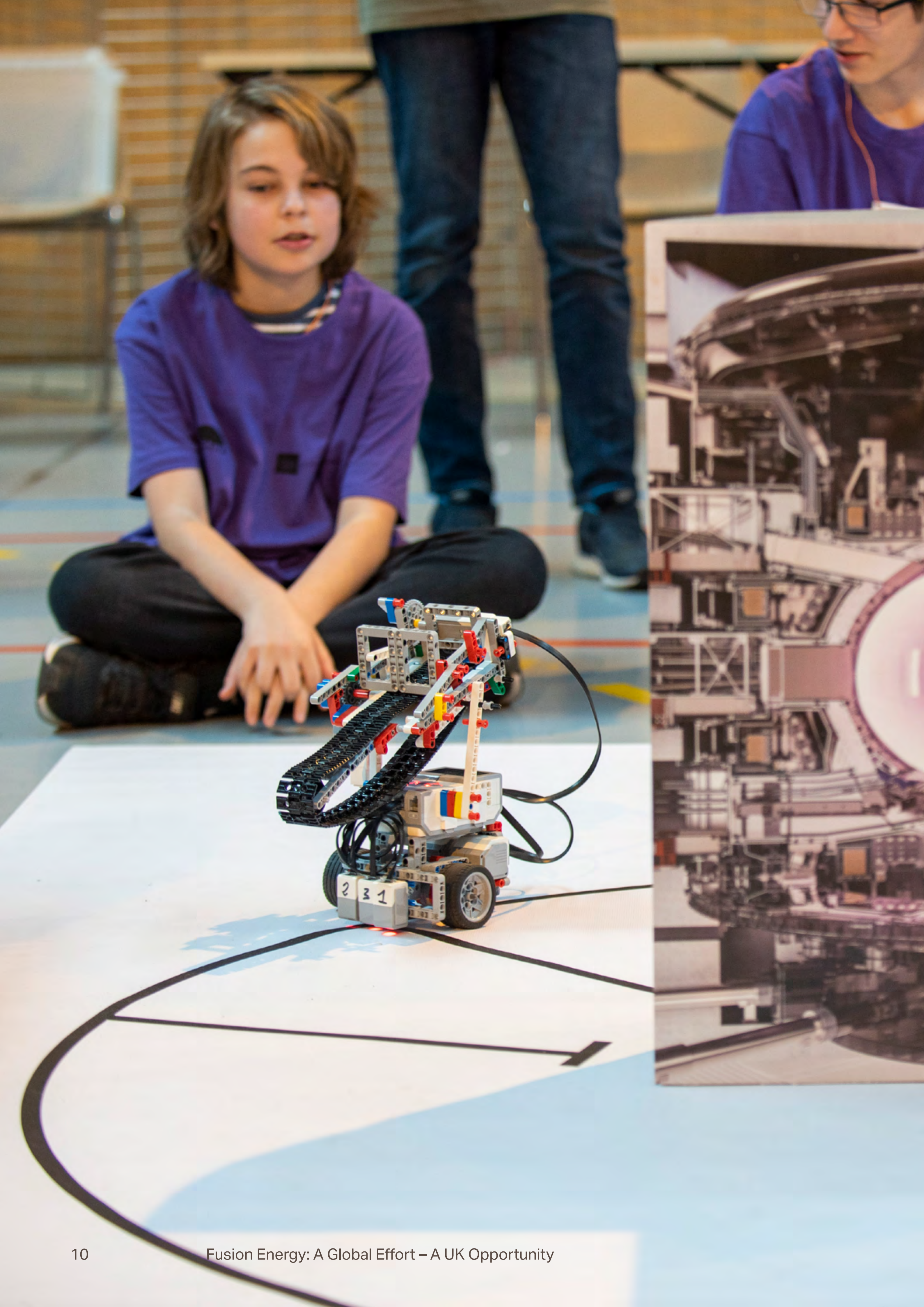
In offering a set of advantages (and challenges) diverse from other sources of dispatchable power, there is therefore a strong argument for pursuing fusion from a diversification perspective, to reduce reliance on a single technology and/or hedge against other longer term limitations of other technologies.

Fusion and heat production

Excluding a radical breakthrough in direct energy conversion from fusion[45], a fusion reactor will act as a heat source for a power conversion cycle – steam or gas turbine. In principle this enables integration of thermal energy storage upstream of the turbine, which would improve the flexibility of the system in responding to varying demand. Such solutions are used by the concentrating solar power industry[46] and increasingly are being investigated by the nuclear fission community[47].

Fusion reactors may also produce large amounts of low-grade waste heat, depending on their configuration. This heat could be harnessed through low temperature cogeneration, for example desalination or district heating. Desalination is more relevant in geographical locations with water scarcity. It is more cost competitive to retrofit existing district heat networks with low-carbon solutions than build new ones. Nevertheless, district heating may heat 5 million UK homes in 2050 under low-carbon energy scenarios[48].

Production of high temperature heat is also a possible additional advantage of fusion, in comparison to most renewables. Potential markets include heat for industrial processes (eg steelmaking) and direct hydrogen production. Such approaches might enable incremental improvement in fusion economics by better matching of both heat and electricity from fusion and improved power availability of the system when demand is variable. This is explored in more detail in later chapters of the report.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A small environmental footprint

The fusion process produces a small amount of radioactive waste through irradiation of the components of the reactor vessel. These components will need to be replaced routinely as a consequence, generating relatively small volumes of radioactive materials with low, or short-lived activity levels.

Fusion reactors are claimed to have high levels of intrinsic safety and very low potential for radiological release. The volumes of radioactive waste produced by fusion reactors are many orders of magnitude lower than from fission reactors. It is impossible for the fusion reaction to grow unchecked, as a disturbance in the plasma will lead to it cooling and the reaction naturally being terminated[49]. Postulated accident scenarios include loss of cooling in the blankets[50]. The main radiological hazard associated with a fusion reactor is the potential for tritium release into the environment[51]. Nevertheless, both the potential for this and the maximum amount of radiological material that could be released into the environment are extremely low[52]. By way of comparison, small amounts of tritium are used in radiopharmaceuticals and hence disposed of as a normal part of safely dealing with hospital waste. Tritiated water is also routinely created and discharged under environmental permit conditions during fission reactor operations.

In analysing the lifecycle greenhouse gas emissions of electricity production from a tokamak fusion reactor, Tokimatsu et al.[53] found them to be slightly higher than nuclear fission. However, 60–70% came from construction and by the time fusion is commercialised it is expected that much of the processes in the construction of such a plant would be largely decarbonised. Fusion does not incur the environmental cost of mining uranium and it does not have to account for the long term management of high level nuclear waste. Although fusion material requirements are high, they are lower than for wind and solar and the land requirements are comparably negligible. Compared to biomass, the fuel is abundant and sustainable.

So even if fusion is not commercialised until the 2050s, there are strong sustainability arguments for developing the technology for deployment in the second half of the Century.

Chapter conclusions

While variable renewables will dominate the electricity grid investments of the future, the demand for low-carbon dispatchable electricity is real and very large. The market for nuclear fusion therefore depends on price. It is not a question of whether there is sufficient demand for electricity from nuclear fusion, it is a question of whether nuclear fusion is able to produce electricity at a low enough cost to meet the demand.

Electricity demand net of variable renewables can be anticipated to fluctuate significantly. Power availability can be achieved through varying heat output, energy storage and/or production of dispatchable resources (eg, hydrogen). Nuclear Fusion should aim to be a dispatchable generator when needed instead of just a baseload (constant) generator.

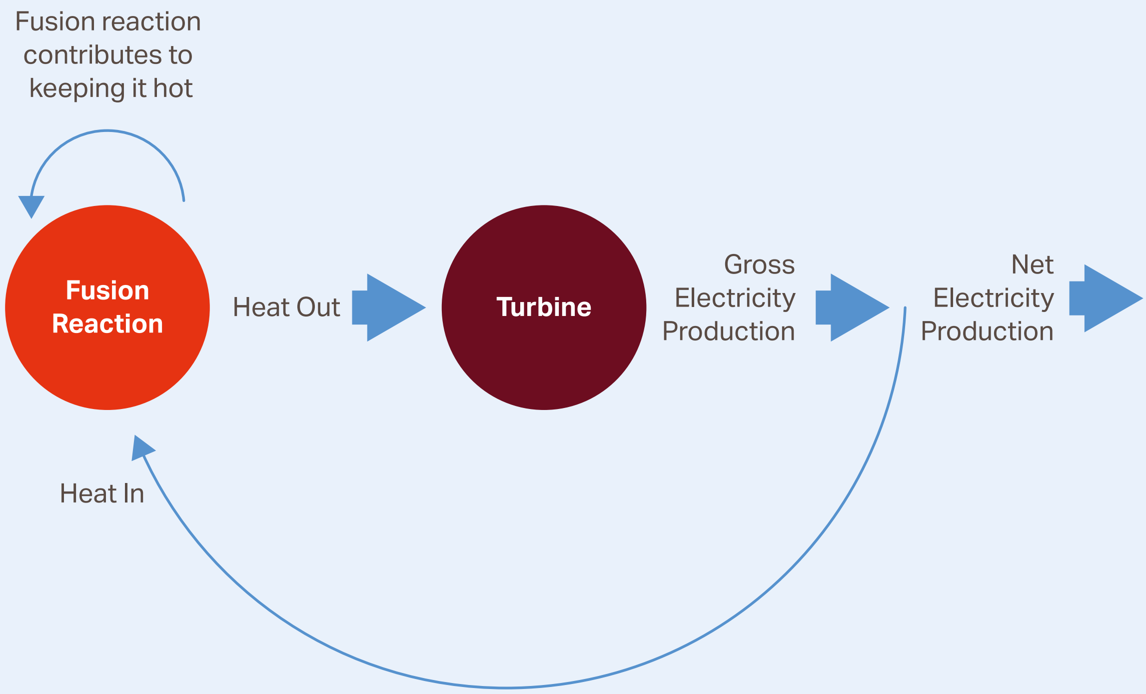
Nuclear Fusion, because of its potentially unlimited sources of fuel, could perform a crucial role in widening access to low-carbon electricity and hence form a key part of the post-2040 electricity generating mix. Given the environmental challenges associated with CCS and bio-energy, in certain regions with opposition to nuclear fission, fusion could be the only technology that can provide large-scale low-carbon power as an alternative to renewables – hence filling a clear market need.

Nevertheless, at a national and global level this is not a role that nuclear fusion can play on its own, due to the timeframes and uncertainties involved with commercializing the technology. Nuclear fusion therefore complements other forms of low-carbon dispatchable generation.

Fusion basics – the gain factor

The key area of fusion research is the scale-up and operation of magnetic confinement to ensure fusion energy is produced at a rate significantly greater than the energy required to heat and contain the plasma. This is known as the fusion energy gain factor (Q). There has been significant progress towards this goal over many decades of fusion research. The current record is held by JET, with Q=0.67. ITER is anticipated to reach $Q \geq 10$ for short periods (minutes).[54] As magnetic confinement technology develops, higher values of Q may be possible. As well as reaching higher values of fusion power gain and longer periods of "fusion burn" (meaning a stable and continuous plasma), ITER will provide crucial experience of operating these systems in an integrated manner.

A fusion reactor produces energy, which must be extracted and converted to electricity. In the most commonly pursued form of fusion, the energy leaves the plasma largely in the form of high energy neutrons from the deuterium-tritium reaction: $D+T \rightarrow {}^{4}He+n$ (see **Figure 1** in the next chapter). These neutrons are slowed down by the blanket surrounding the tokamak releasing heat. The blanket typically also contains lithium-6 (${}^{6}Li$), which is used to produce tritium to be used as fuel, through the reaction: ${}^{6}Li+n \rightarrow {}^{4}He+T$. Systems are required to recover and account for tritium.



Chapter 2
Fusion technology options

This chapter includes an overview of:

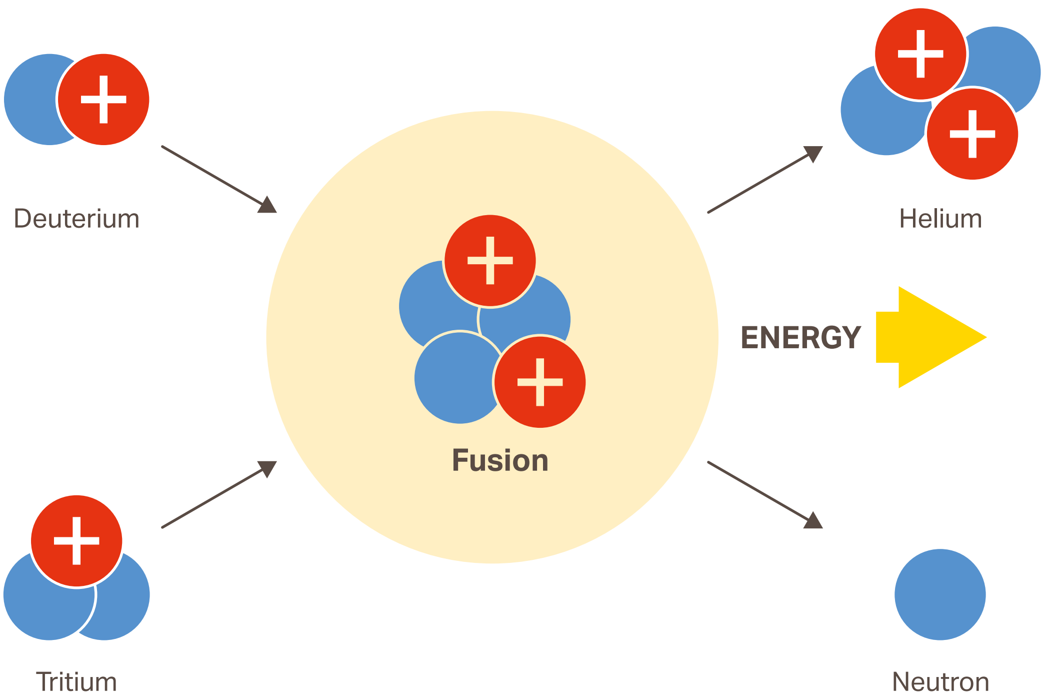
- The JET-ITER-DEMO large tokamak research programme
- Compact tokamak designs that are being pursued
- Alternative (non-tokamak) fusion concepts

Introduction

Useful net energy may be produced by the fusion of nuclei at high temperature and pressure and this is the foundation for the push towards fusion power plants. The most commonly used isotopes are those of hydrogen, with deuterium-tritium (D-T) being the most promising combination as the temperature required to achieve fusion is lower than alternatives. Lower temperatures make the engineering challenges less burdensome and this is why D-T is the reaction of choice for most fusion commercialisation efforts. Deuterium occurs naturally and is abundant. Tritium is currently produced by fission reactors, but in the long term can be produced by fusion reactors.

The most-pursued approach in the development of fusion power is magnetic confinement fusion. Most magnetic confinement devices are toroidal, including tokamaks (See page 20 – The elements of a Tokamak Fusion Reactor). The most well-known devices, the Joint European Torus (JET) in the UK and the International Thermonuclear Experimental Reactor (ITER), are large tokamaks.

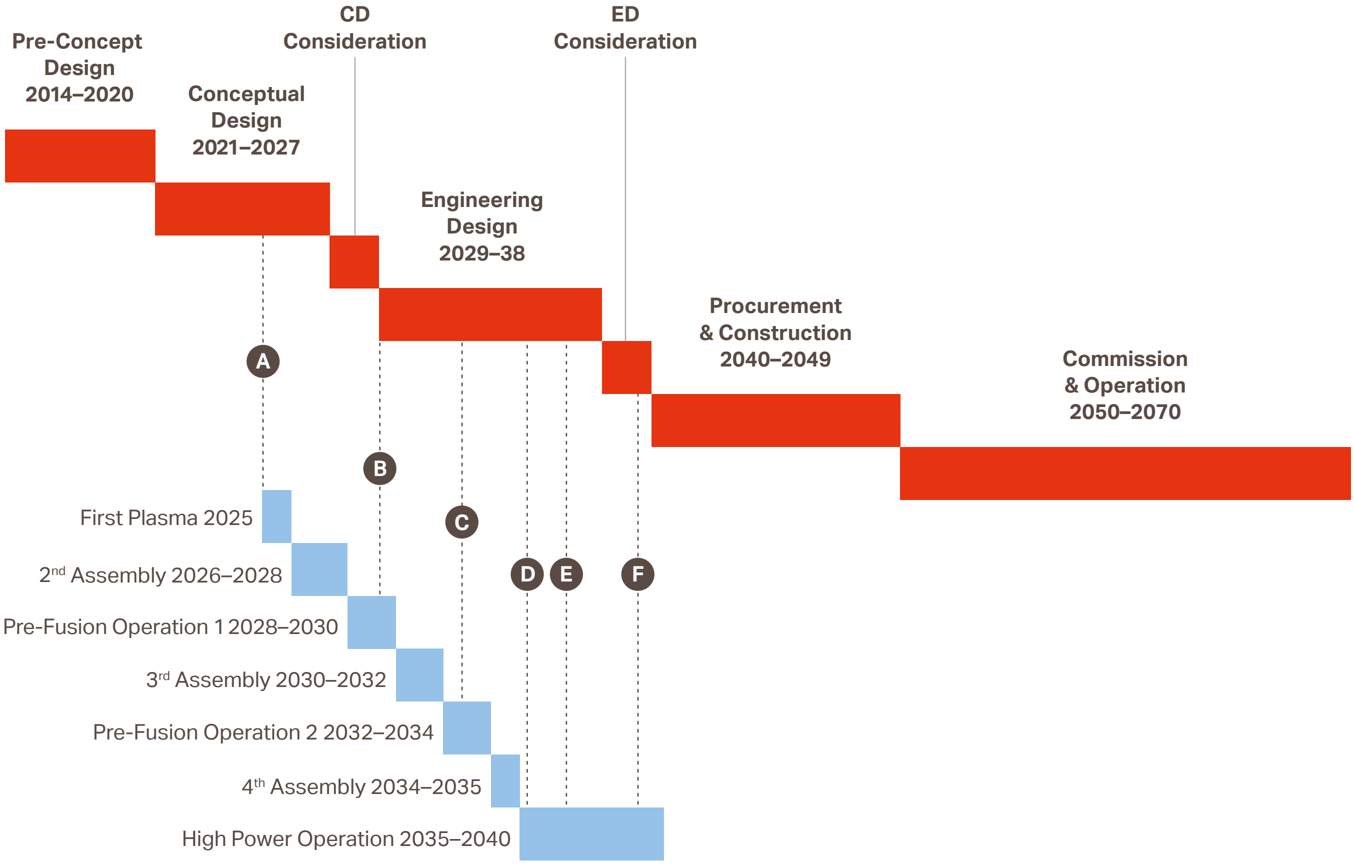
Figure 1: The basics of a fusion reaction



The current international fusion programme is centred on ITER, which aims to demonstrate fusion feasibility and provide the basis for a subsequent demonstration commercial fusion power plant (referred to as DEMO).

ITER experiments over the period 2025 to 2035 should progressively provide proof of performance and data for the design of the DEMO power plant – as shown on **Figure 2** below[55].

Figure 2: The path from ITER to DEMO



A
- Validated assembly
- Integrated design
- Testing & comission
- SC magnets
- W fabrication validation

B
- Integrated diagnostics validation
- ECRH performance
- Disruption characterisation
- Divertor remote
- Maintenance validation

C
- H-mode transition threshold
- Validation of ELM control & disruption mitigation
- NB & ICRH performance
- Diagnostics validation
- Validation of BB fabrication

D
- Bum scenarios
- Bootstrap fraction
- First wall heat loads
- Tritium plant validation
- Full H&CD validation

E
- TBM validation
- Operational scenario refinement
- Q=10 (short pulse)

F
- Q=10 (long pulse)

Alternative routes to commercial fusion are being developed at a smaller scale to ITER. Some more recent proposed designs, including the devices developed by Tokamak Energy and the UKAEA's Spherical Tokamak for Energy Production (STEP), are investigating more compact reactors, as this is seen by some to improve the economic viability of fusion and to quicken the pace of development.

The basics behind these tokamak technologies are explored in this chapter, as well as more speculative alternative routes to producing useful energy from fusion.

Large tokamaks

In the early 2000s, the European Power Plant Conceptual Study (PPCS) identified four concepts – A, B, C and D – all sized to produce 1,500 MWe from 2,500–5,000 MW of fusion power (**Table 1**).[56] These span near-term and longer-term technologies. Near-term designs are characterised by less ambitious physics and materials choices, but have lower performance in terms of power plant compactness, energy gain and cycle efficiency. European plans for a demonstration fusion power plant, sized for 500 MWe, are currently focussed on nearer term technologies[57], resembling PPCS A and B which can achieve efficiencies in the 31–36% range.

A key consideration for governments and companies investing in fusion is whether to move ahead with developing a power plant based on more proven technology, or whether to pursue further R&D with the aim of achieving a fusion power plant with superior performance, which in turn will improve its economic viability. In the JET-ITER-DEMO programme, this could be expressed as: "At what point do we freeze the design of DEMO and begin the detailed design and construction of the demonstrator?"

Table 1: European Power Plant Concepts[58]

	A	B	C	D
Major radius in metres (measure for tokamak size)	9.55	8.6	7.5	6.1
Plant efficiency	31–33%	36%	42%	60%
Power conversion cycle	Steam	Steam	Gas	Gas
Technology readiness	Highest	→	→	Lowest

During the last 20 years, the main thrust of fusion research has been tokamaks of larger and larger size as this has been required to investigate and demonstrate sustained fusion with high energy gain, as only tokamak designs have demonstrated sustained fusion burn, ie maintaining a continuous plasma that can provide useful energy continuously. The Tokamak Fusion Test Reactor[59] (TFTR) in the US and JET in the UK have shown sustained if only short duration fusion burn in the 1990s, though with energy gains less than one – ie less than break-even. While Korea Superconducting Tokamak Advanced Research[60] (KSTAR) in Korea and Experimental Advanced Superconducting Tokamak[61] (EAST) in China have made similar achievements in the last few years. ITER is a much larger fusion experiment being built in France. It seeks to demonstrate much higher fusion power (500 MW) with a much longer burn duration (400–600 s) and a positive fusion energy gain ~10, whilst also demonstrating tritium breeding which is fundamental to the fuel cycle.

For size comparisons, the much lower power (500 MW fusion power) ITER has a major radius of 6.2m[62] and STEP (see below) is anticipated to be smaller than ITER by virtue of being a spherical tokamak.

All these fusion experiments have relatively low power density and high aspect ratios (ratio of major to minor radius), between 3–4 and high strength field magnets to contain the plasma. Studies of future fusion power plants to follow ITER, both in the US[63] (ARIES) and Europe[64,65] (DEMO and its variants) make use of this same design strategy – large device and high aspect ratio.

Before either DEMO or ARIES is built, fusion feasibility will have been demonstrated by ITER. Fusion feasibility includes significant gain ~10 and much longer periods of fusion burn 5–10 minutes than at present 20–100 seconds.

The proposed designs of demonstration power plants are large in size (6–9 m diameter), have high aspect ratios and large power outputs (more than 500 MWe). This large scale design strategy is considered by many[66,67,68] to be the most practical and economic choice for fusion power. Other important design factors will be the operating profile – pulsed or steady state, the availability of the plant and power conversion cycle efficiency.

Flexi DEMO is a proposed European fusion power plant that if eventually approved would be a successor to ITER. It is large (8.4 m major radius) with a high aspect ratio (3.1) and a high field strength (5.8 Tesla) from its low temperature superconducting coils. It is proposed to start operation in 2040 with a target fusion power of 2 GW and electrical output of 400 MWe. Initially DEMO will operate in pulsed fusion mode and use existing wall and divertor materials and have a low power conversion power cycle. There are improved versions of Flexi-DEMO being planned that operate in steady state mode, make use of advance materials and perhaps higher efficiency power cycle, but these will take another 20 years to come to fruition.

Alternative tokamak designs for fusion energy development

Large designs have very high capital costs – tens of billions of dollars – and their scale and complexity has slowed the pace of fusion development. The ITER project is expected to enter into operation in 2025, some 20 years after initial R&D studies were commenced. This issue led to the exploration of two different tokamak design concepts to speed up development and perhaps also reduce cost:

1. Radically smaller fusion devices.
2. Spherical devices with lower aspect ratios (< 2).

Both ideas have been enabled by the pace of developments in superconductivity research meaning that much higher magnetic field strengths are achievable from new superconducting magnets. The proponents of these fusion technologies[69,70] expect that these smaller devices – eg ST150, STEP and ARC – with their higher power densities will reduce cost, accelerate development timescales and shorten build schedules.

High field tokamaks have been investigated at MIT for many years.[71] They explored a number of upgrades to the Alcator-C fusion experiment, higher toroidal fields of up to 8 Tesla. Commonwealth Fusion's SPARC experiment is based on these ideas. It seeks to show that a compact (3m radius), high aspect ratio fusion power plant: ARC[72], could operate effectively with much higher power densities and because of its molten salt blanket coolant and a gas power cycle, achieve a higher level of efficiency (36%).

Spherical tokamaks such as STEP and the ST150 aim to improve compactness and hence drive lower manufacturing and construction cost by nature of their size and shape. A spherical design increases the materials challenges for the narrow central column. Such design choices are possibly higher risk and higher reward – such a fusion reactor could be potentially more competitive if the technology can be proven. The scientific community is divided on the best technologies and this is one of the driving forces behind recent increased investments in a diverse range of fusion energy concepts.

Although the design of the UKAEA's STEP is not yet fixed, the aims of STEP are to have a much lower aspect ratio (below 2) and it will be smaller in size than ITER.[74]

ARC (Commonwealth Fusion) is a small (3.3m major radius), compact fusion power plant with a simplified design and rare earth high temperature superconducting magnets that provide very high magnetic fields (9 Tesla), with a novel liquid immersion blanket and demountable vessel modules. It is designed to produce 500 MW fusion power and 200 MWe of electricity with a range of possible high efficiency power cycles.

STEP (UKAEA) is a compact spherical demonstration fusion power plant (2040). Details of the design are yet to be determined but it is likely to have high fields from superconducting coils, higher power density than ITER and initially pulsed operation and a low temperature power cycle similar to DEMO. Because of material limitations, major components will have to be replaced every few years impacting both operating cost and power availability, though this could improve as better structural, blanket and divertor materials become available.

Spherical tokamak advocates, such as Tokamak Energy in the UK, claim high fusion gain (~10) can be achieved with low aspect ratio at a much smaller size and lower fusion power (150 MW) – with high field 4 Tesla spherical devices[75]. These claims are based on experiments conducted on NSTX in US and MAST in the UK. They plan to confirm their prediction with their ST40 experiment before constructing a larger design of fusion power plant, ST150.

There are also many other theoretical ways of achieving fusion. The very large scale, the long duration and the expense of the current fusion programmes based on tokamaks and magnetic confinement have stimulated a wide range of alternative fusion concepts, some of which are being actively developed.

ST150 (Tokamak Energy) is a very small (less than 2m radius) spherical demonstration fusion power plant (2030+) with high temperature super conducting rare earth magnets, high power density and designed for long pulsed operation. More detail on materials lifetime and power conversion cycle, both of which are important to plant economics, will need to be demonstrated to realise these potential benefits.

Alternatives to tokamak fusion reactors

ARPA-E advanced fusion projects[76]

ARPA-E ALPHA programme is funding nine advanced fusion concepts. Each design is small in scale and unconventional, some using proton-boron rather than D-T reactions, and each is seeking to provide low cost energy from fusion. The four leading concepts are:

- Stabilized Liner Compressor (SLC);
- Plasma Jet Driven Magneto-Inertial Fusion (PJMIF);
- Staged Z-Pinch by Magneto-Inertial Fusion Technologies, Inc. (MIFTI);
- Sheared Flow Stabilized Z-Pinch (SFS Z-Pinch).

These small devices aim to establish the viability of novel fusion concepts quickly. Though none has yet achieved fusion conditions, design studies of possible power plant concepts have been completed. For 150 MW of electric power, the range of estimated overnight cost of the four pre-conceptual fusion power plants is between $0.7 billion and $1.93 billion (in 2016 US dollars). The designs are not yet adequately developed and detailed to be used to estimate overnight costs for potential larger capacity plants (eg 1 GWe range). Nevertheless, their specific capital costs could be in the range $4,700/kWe and $13,000/kWe.

Some of the projects are now moving to larger scale feasibility experiments using mainly private funding, with the aim of beating tokamak designs to commercial fusion power. Two are of note:

- **Magnetized target compression fusion – General Fusion.** General Fusion's concept[77] has some similarities with the Stabilized Liner Compressor (from NumerEx). In their pulsed design, a super-heated plasma is injected into a cylinder surrounded by a rotating wall of liquid lead-lithium. Pneumatic pistons drive the liquid metal wall inwards compressing the plasma into a ball to achieve fusion conditions. Energy released by the fusion reaction heats the surrounding liquid metal and is used to drive a steam turbine.

General Fusion's focus has been developing parts of the concept: piston compression, high temperature (5 million degree) plasma injectors and its rotating liquid metal wall. Funded by private investors, they plan to build an experiment using deuterium in the UK, as a prototype for a later larger D-T fusion power plant.[78]

- **Field-Reversed Concept – Helion Energy.** Helion Energy's FRC design[79,80] accelerates pulses of ions of deuterium and helium3 before compressing them magnetically to achieve fusion conditions. Helion is seeking to produce a small fusion device without the complications and technology needs of tokamaks. Because they are using helium they require higher temperatures for fusion. Unlike D-T fusion, most of the energy is released as ions and Helion aims to capture this energy directly by the magnetic field. They have achieved temperatures of several keV and fields of 8 Tesla. Now they are building a proof-of-concept experiment to achieve temperatures >25 keV – close to fusion conditions.

Inertial fusion

Inertial fusion using lasers has been investigated in the US National Ignition Facility (NIF). It uses lasers to implode a D-T target to achieve the very high pressures and temperatures necessary to achieve fusion conditions. NIF uses 192 lasers operating together to provide 500 TW in a very short pulse. During 2012 NIF achieved fusion conditions but not with enough fusion gain to be useful. Most recently, in 2021, they reported achieving output of 70 percent of the laser energy delivered to the target as fusion energy.

A completely different form of inertial fusion is being investigated by First Light Fusion in the UK. They use high pressure obtained in collapsing bubbles in a liquid – the so-called "sonoluminescence" effect. Based on research done at Oxford and building on earlier US work, First Light uses shock waves to collapse bubbles – potentially to achieve fusion conditions. This project is at an early experimental phase but is already being claimed as a simpler way of achieving low-cost fusion. The low cost claim originates from its simplicity and because it can be done at a small scale.[81]

The elements of a Tokamak Fusion Reactor – ITER explainer

The ITER Tokamak

The tokamak is an experimental machine designed to harness the energy of fusion. ITER will be the world's largest tokamak, with a plasma radius (R) of 6.2 m and a plasma volume of 840 m³.

Magnets

Ten thousand tonnes of superconducting magnets will produce the magnetic fields to initiate, confine, shape and control the ITER plasma.

Vacuum Vessel

The stainless steel vacuum vessel houses the fusion reactions and acts as the first safety containment barrier.

Blanket

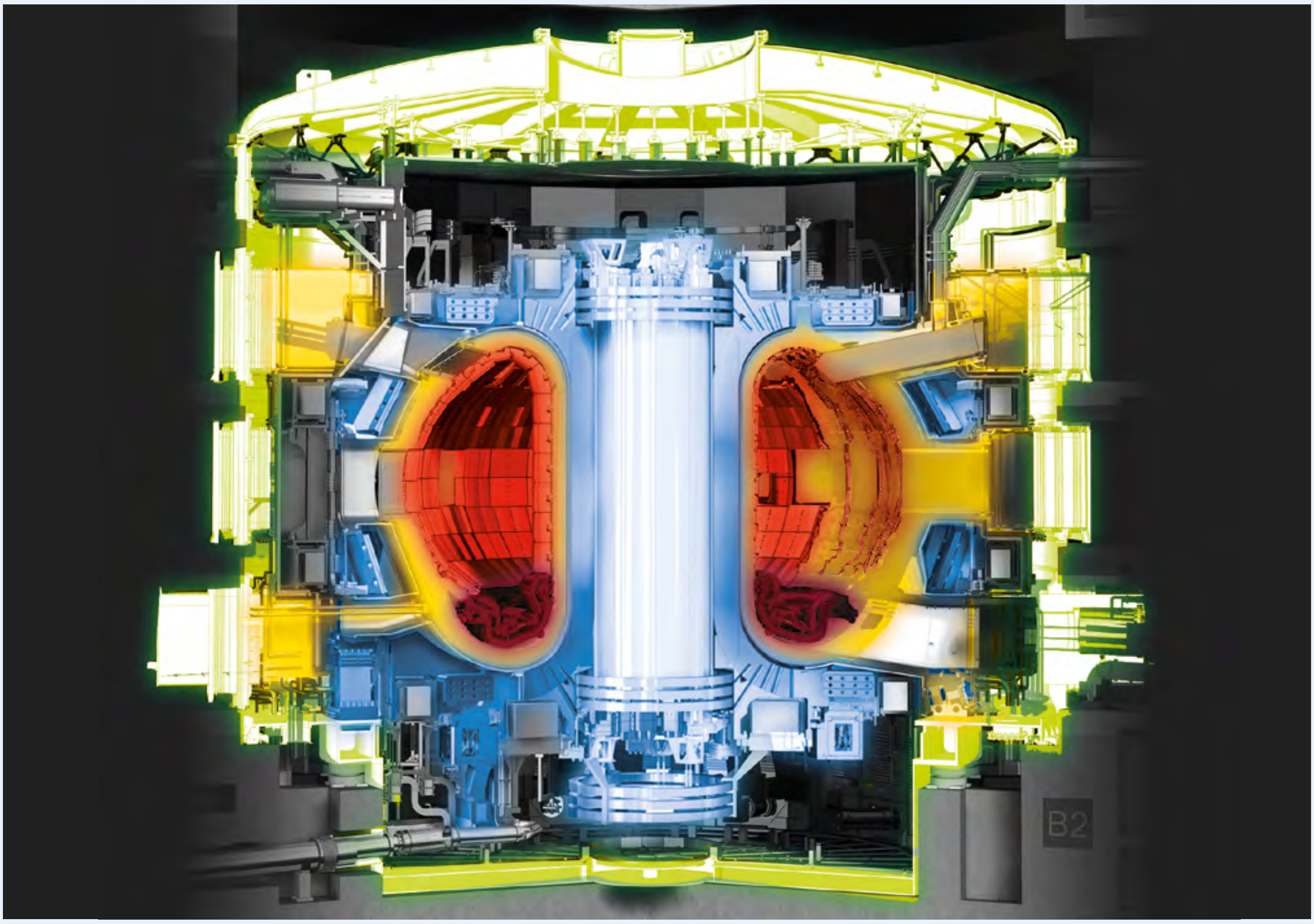
The blanket shields the steel vacuum vessel and external machine components from high-energy neutrons produced during the fusion reaction.

Divertor

Positioned at the bottom of the vacuum vessel, the divertor controls the exhaust of waste gas and impurities from the reactor and withstands the highest surface heat loads of the ITER machine.

Cryostat

The stainless steel cryostat (29 x 29 m) surrounds the vacuum vessel and superconducting magnets and ensures an ultra-cool, vacuum environment.



Chapter 3

Developing and deploying novel energy technologies

This chapter includes an overview of:

- The path from scientific experiments to commercial fusion power plants

The gap between R&D and commercial deployment is sometimes referred to as the Valley of Death. Many new technologies languish in the conceptual design stage because further funding, either from Government or private investors, cannot be found. This is particularly the case for large-scale, complex projects that require a significant outlay to build a commercial-scale demonstration plant. This is a risk for the fusion sector. This Chapter outlines a path to commercial fusion, from scientific experiments, to demonstration plants, to a first-of-a-kind (FOAK) commercial power plant. Refer to Chapter 5 for the potential financing options for each phase of development.

> If an engineering demonstrator is successful, the next step is typically a full-scale system that can then be deployed commercially.

The stages of fusion development and deployment

The development and deployment of complex systems such as fusion power plants can be clustered in four main phases, each phase with its costs, goals and stakeholders. In this Chapter, ITER and DEMO will be used as examples as this is the most well-established path to fusion energy.

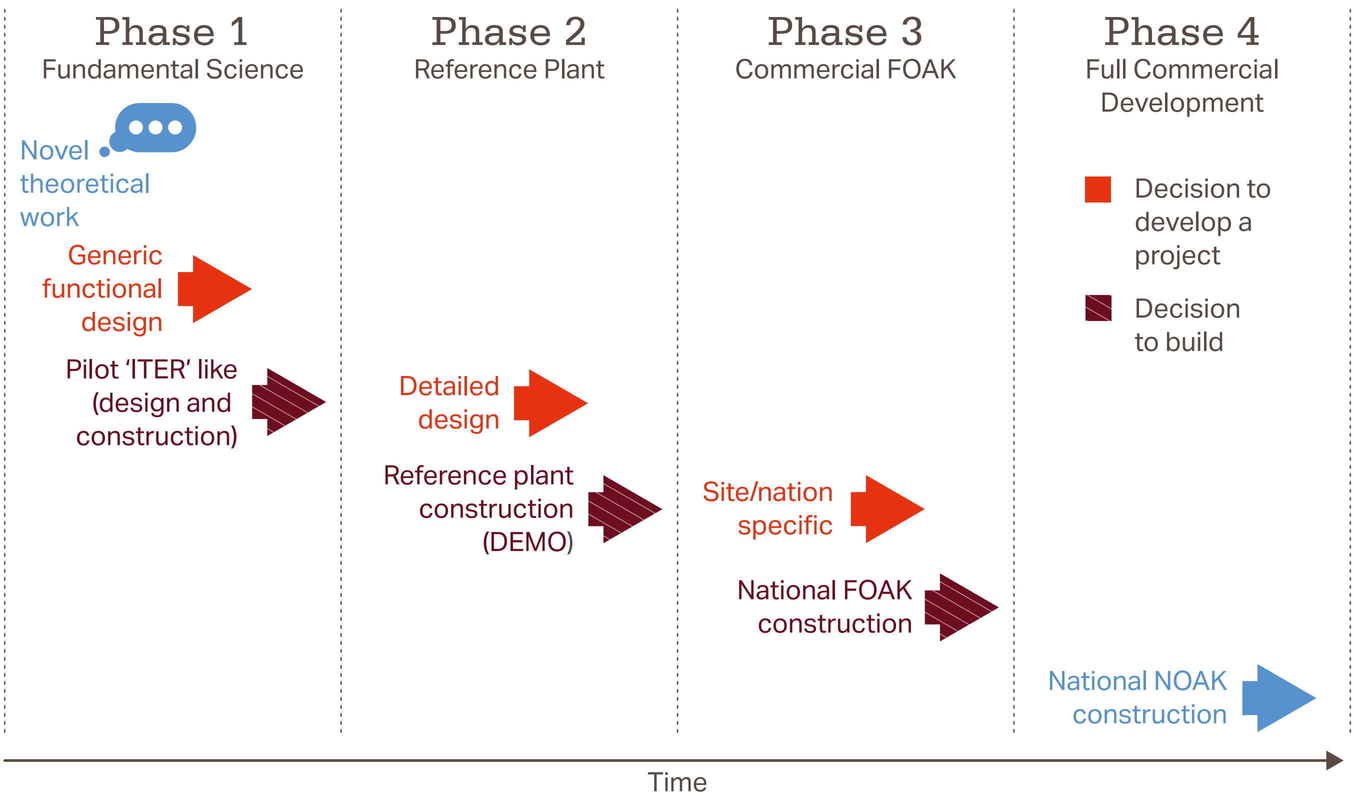
Phase 1 – Fundamental technology. The goal of this phase is to demonstrate a novel technology. It includes theory, modelling and experiments aimed to define the basic approach – to show that in principle it works. This is the current stage of fusion, with many large experiments around the world exploring the physics of fusion with a view to demonstrating sustained fusion energy gain in ITER during the early 2030s. ITER won't produce any electricity but will test critical aspects of the design, such as net production of energy and the possibility of sustaining plasma and addressing the key materials issues.

Phase 2 – Demonstration power plant. This stage aims to practically demonstrate sustained production of power from fusion. DEMO will be a power plant derived from the lessons learned through ITER. In this phase, engineers and scientists will run a series of experiments to better develop the technology. This plant will produce electricity, but it will have a low commercial value because of the experimental nature of the project and high associated construction and operating costs.

A fusion prototype needs to demonstrate essential performance and operating characteristics but not industry standards of power availability or net efficiency. Similarly in the nuclear fission sector, the Prototype Fast Reactor at Dounreay was an engineering demonstrator for nuclear fission fast breeder reactor technology.

If an engineering demonstrator is successful, the next step is typically a full-scale system that can then be deployed commercially.

Figure 3: A roadmap to commercial fusion



Phase 3 – Commercial FOAK (First of a Kind). This stage will aim to leverage DEMO power plant experience to design and build a FOAK commercial unit and establish that a scale up of the system works, and to gain operating experience to validate the behaviour of the whole system.[82]

This unit is expected to produce electricity that will be sold on the market. It is likely that this will not be economically viable per se since it will require substantial one-off design and construction costs. Moreover, the units might not be "fully reliable", requiring considerable downtime and maintenance to fix problems while emerging and may also need an extended commissioning phase. However, this unit is important because it involves a utility operating a fusion power plant in a realistic manner. This unit is critical since many investors are reluctant to invest in a novel commercially untested new technology. Large and complex infrastructure have been delivered over budget and late in the past, which makes new technology projects un-investable.

Phase 4 – Commercial Power Plants. Building on the experience of the FOAK, several other units might be built, incorporating key lessons learned in both construction and operation. These commercial units might be more economically viable, particularly if more units are built in the same nation and, ideally, on the same site. Research has shown that the cost of a complex system can be decreased by the so-called "economy of multiple" – building the same design repeatedly, ie standardisation.[83,84] However, there are practical limits in this copy-paste approach to power plant design, particularly for some of the large GW-sized fusion power plants that are being considered.

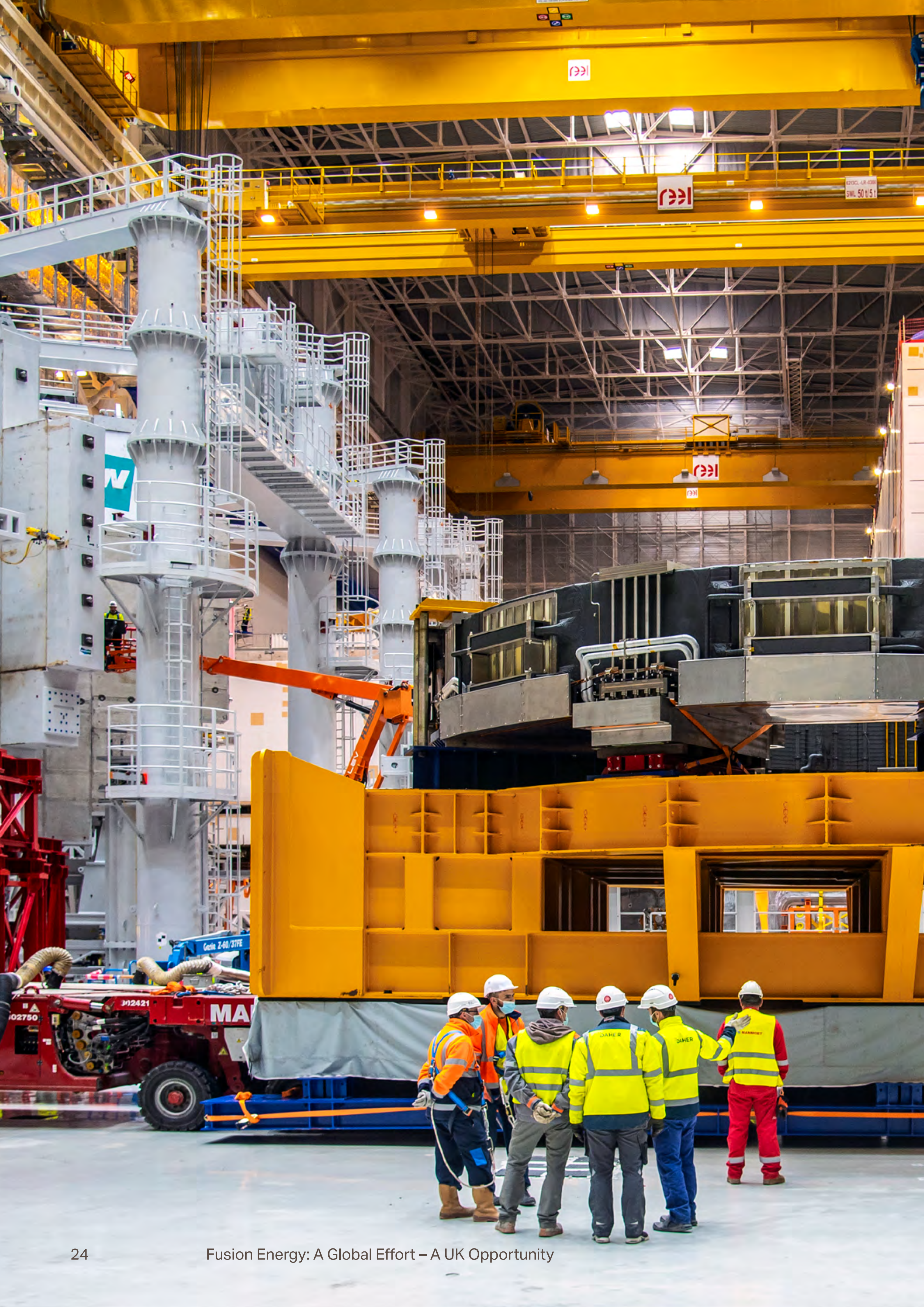
The first challenge is that this replication is extremely difficult across countries since each country might adopt its own safety and technical regulations and also require more local content. Also, learning across projects even in the same country can be challenging. Competencies developed by managers technicians and specialists need to be transferred between teams and projects – which is often not practical or commercially possible. Moreover, even inside the same country, each site has its specific characteristics, such as access to water for cooling. These elements are a barrier to the "economy of multiple" that should be the goal of this phase to increase the fusion power plant's commercial viability.

Fusion is in Phase 1 of development. This will continue until ITER demonstrates D-T fusion in 2035. The UK, like some other countries, is planning a demonstration plant (STEP) to be completed in 2040 – Phase 2. Commercial plant will follow with a planned larger FOAK – Phase 3, with follow-on commercial power plants – Phase 4, later.

The question is: When to freeze the design of DEMO? Even if the design of DEMO aims to be modular in nature, the choice of technology for the engineering demonstrator does not necessarily support the performance of a later demonstrator with another more advanced technology. This applies to the configuration of the magnetic confinement, the blanket technologies and the power conversion cycle technologies. As noted, the choice of more ambitious technology could lead to bigger payoffs in the long term but with higher risks of delays or non-delivery.

Current European studies of DEMO are focused on near-term conservative technology choices that allow a design freeze in the mid-2030s but have low power plant efficiency.

Ideally, multiple concepts would be pursued in parallel, as was the case with nuclear fission during its early development. This paradigm will likely be pursued in the US with its larger resources and also perhaps around the world, but the UK will likely need to focus resources on a smaller suite of technologies, while maintaining the flexibility to take advantage of new technologies and mitigate issues as they emerge. This strategy affects the challenges in developing the supply chain for fusion systems and components.



Chapter 4
Cost of fusion energy

This chapter includes an overview of:

- Cost estimates for fusion power systems
- Cost uncertainty in large energy projects and the reasons for this uncertainty
- The ways in which costs can be reduced

Introduction

There is relatively little information available on the costs of fusion as an energy source. This is because all the current devices (and in future ITER) are experiments that seek to demonstrate the physics of fusion and have costs that reflect state-of-the-art stage developments. Also, these do not include the costs of power generation equipment, nor the systems required to produce and handle tritium. Fusion power system codes calculate the effect of different design options and estimate their effect on both system performance and economics. The two main codes are ARIES[85] in the US and PROCESS[86,87] in Europe, though neither detail how the cost estimates are derived and based. Earlier, more detailed models of cost of large fusion systems have been recently updated[88], and tied back to the costs of ITER major systems and components. These models are also extended to smaller fusion systems.[89] It seems that all current cost estimates are to some extent based on ITER costs – using these for the fusion specific equipment costs and adding estimates of related power generation equipment for the balance of plant. ITER cost estimates are reduced by a factor to account for them being state-of-the-art and experimental. They are adjusted for difference in scale etc. using power plant scaling based on power output. For novel fusion equipment and high field magnets, bespoke scaling methods based on either fusion power level or magnetic field strength are employed.[90,91]

The current early stage of development of fusion energy means that all the estimates of both overnight capital cost and of energy cost for fusion are subject to large uncertainties. Costs may be higher than those discussed below. On the other hand, technical and manufacturing innovation may allow costs to be reduced more rapidly.

> Estimating the cost for complex systems and infrastructure is challenging because there is a lack of similar projects for which comparable cost data exists.

Cost & revenue estimation of complex energy infrastructure

Cost estimation

Estimating the cost for complex systems and infrastructure is challenging because there is a lack of similar projects for which comparable cost data exists. The first challenge is in estimating the overnight capital cost, which is the cost of building a plant excluding time-related outlays like financing. This includes direct costs (such as direct labour, material and equipment) and indirect cost (such as indirect field costs, design services, construction management services) and contingency.[92] Estimating direct cost when the design is not completed is problematic; for instance, the estimator needs to assess the cost of equipment (eg magnets), material (eg concrete), and labour (eg welding). Also, elements such as "rework" (common in building complex systems) need to be estimated. Key cost drivers, such as labour productivity or the effect of complying with safety regulations also need to be considered.

Novelty, complexity and scale are all potential risks to programmes which in turn can lead to cost overruns. These types of projects are perceived as high-risk by investors, and so a higher rate the return is expected. For projects with long development times and construction schedules, financing can comprise as much as 50% capital cost.[93]

For large capital-intensive projects, the type of investor is also important. Governments can borrow money at a relatively low rate (eg the UK Government's 10-year bond yield currently is about 1%). Private investors borrow money at higher rates. Chapter 5 shows the sensitivity of the electricity price in respect to changes in discount rate, which broadly is a proxy of the cost of borrowing.

Accurate estimates for operation and maintenance costs do not exist for fusion. The number of staff to operate a commercial fusion system, what maintenance would be required, which parts need to be replaced and how often – are all uncertain. Phase 2 projects will provide some data for this analysis, but reliable data will be available only years into Phase 4, with many fusion power plants operating (refer back to Chapter 3 for an explanation of development phases).

Moreover, different countries have different construction costs, even for the same (or very similar) designs of power plants.[94] For instance, the 2 EPRs built in China (by Taishan Nuclear Power Plant) cost 50 billion yuan (US$7.5 billion)[95], while the similar two EPRs being built in the UK (Hinkley Point) have estimates now in the range of £22–23 billion (US$31 billion).[96] Labour costs, supply chain readiness and experience, borrowing costs, labour productivity and project know-how, safety and technical regulation all have an impact on capital cost.

Levelised Cost of Electricity (LCOE)

LCOE is used to compare plant-level energy costs of different types of power plant. LCOE is the price of electricity that would cover all the immediate and long term costs of production.

For fusion, the amount of electricity generated by a plant is important. This depends on three main parameters: size of plant [MW], lifespan [years], capacity factor [%]. The size of the plant is a design choice and is predictable. For a new technology like fusion, the other parameters are more uncertain. Engineers estimate the plant lifespan and, in cases such as nuclear reactors, this is linked to a licence duration with any expected extensions. Lifespan is dependent on key components and the ageing of their materials. For example, US nuclear reactors were originally designed for a life of 40 years (limited by knowledge of vessel ageing). They are now performing well and with improved vessel material ageing knowledge that they are being licensed for periods of 60–80 years. Other power plants have shorter life-times because of a material degradation, or an accident, or poor performance making them uneconomic.

Capacity factor – meaning the actual electricity produced over a period of time compared to 100% maximum output over this time – of a novel technology is difficult to estimate but for the case of fusion is important because of its high capital cost. Although nuclear fission capacity factors were initially low, well performing fission plants today have capacity factors significantly above 90%. However, novel technologies are often far less reliable. They could have considerable downtime to maintain or repair faulty systems. For instance, the Phenix fast reactor (an engineering demonstrator) and the larger Superphenix reactor (a performance demonstrator) in France had capacity factors of 40% and 8% respectively, making the operations of these demonstration or FOAK reactors extremely uneconomical.[97]

Why cost overruns and delay are common in the development of novel technology

There are two distinct characteristics of the development and deployment of new technologies. Firstly, the cost of state-of-the art test facilities may not be a good indicator of the cost of the technology as it matures. Secondly, large and complex infrastructure projects often are delivered late and over budget.

ITER and its precursors are R&D projects. Their focus is on pushing back the frontiers of science. This involves developing new technology and materials, as well as significant modelling of the physics. Cost effectiveness is not the priority. Also, these experiments are usually unique, they take many years to come to fruition and they employ large numbers of engineers and scientists. Hence, costs estimates of demonstration and commercial power plant based on the experimental project costs are problematic. Nevertheless, the potential scale of change in cost as new technologies move from development into deployment can be seen from the historical cost trends of early fission projects[98]. In the US, specific capital costs fell by 81% for 18 demonstration reactors over the years 1954–1968. Also, in Japan the cost of 11 early reactors fell by 82% in the years 1960–1971 and in France costs of their first seven gas-cooled designs also fell by 82% in the years 1957–1966.

Project cost and time slippage occurs to Phase 1 projects because of their novelty (see ITER), and is not infrequent for the later Phase 2 or 3 projects (refer back to **Figure 3** in Chapter 3 for an explanation of the development phases). For instance, cost overruns of reactors built in the USA in the 1980s after Three Mile Island, or the EPRs under construction in Europe have been as high as 200%.

The literature discusses several reasons for budget overruns and delays. Professor Bent Flyvbjerg asserts that budget overruns and delays are tied to behavioural psychology:[99]

- Optimism bias: a cognitive predisposition that most people have, in which they judge future events in a more positive light than is warranted based on actual experience (see also planning fallacy).
- Strategic misinterpretation: deliberate overestimation of benefits and underestimation of costs to increase the likelihood that a project gains approval and funding.

Prof Peter Love has explained how overruns can be the result of "changes in scope and definition between the inception stage and eventual project completion".[100] Strategic and economic decisions taken for a project influence how an organisation processes information, which affects the way they manage risk. So, (inevitably) scope changes, mistakes and rework in construction can explain much of the cost overrun.

A recent article[101] detailed a study about sources of nuclear power plant construction cost overruns in the US over the past five decades:

"Indirect costs caused most (72%) of the cost increase during period 1 (1976–1987), in particular the indirect expenses incurred by home office engineering services […], field job supervision […], temporary construction facilities […] and payroll insurance and taxes. A majority of these costs are not hardware related and are rather "soft" costs. […] Decomposing individual plant costs, we identify declining labor productivity as a major driver of cost increase over time, which we study mechanistically through a case study of the reactor containment building."

One should be extremely circumspect regarding the economics of novel technologies and their cost estimation in particular. This is true for technologies based on proved technologies (such as fission reactors) but is particularly applicable for novel technologies such as fusion. It is difficult to estimate the cost even based on proved technologies, therefore it is extremely challenging to assess the economics of unproven technology with only a very preliminary design, using an uncertain financing scheme, in the future.

Future price of electricity

The market price of electricity will be key to the economics of fusion. Commercial fusion reactors will likely not be available before 2040 and estimating the price of electricity during their expected operating lifetime 2040–2100 is extremely challenging. However, innovative and developing energy infrastructure seldom relies on purely market prices. Governments often put in place policies to support new or important technologies, such as Contract for Differences[102] (CfD) in the UK, which are being used to support both wind farms and new nuclear power plants. These policies can make commercially viable power plants that otherwise wouldn't be economically feasible. Also, policies can be put in place to increase the cost of other technologies, for instance, taxing petrol and diesel fuel (more than 60% of the fuel price in British cars is taxation). Increasing fuel or carbon tax makes other technologies comparatively cheaper (eg electric cars).[103] By the 2040s, it is possible that carbon taxes may be both widespread and high, with perhaps even a border taxes based on the embedded carbon emissions from manufactured goods. This would make energy generation from fossil fuels much more expensive, and carbon-free energy technologies more competitive.

Cost estimates for fusion power systems

Assessment of published information shows that the most detailed and most cited estimates of overnight capital costs for fusion are those published periodically by Ward[104] from UKAEA using their PROCESS code. More recently published studies by Entler[105] look at the costs of an advanced technology fusion power plant DEMO2 but there are concerns about how his costs have been inflated from the baseline in PROCESS. Lee[106] has looked at the effect of high temperature superconductors on energy costs, and how these scale with power output. Van den Berg[107] takes a different route in his cost estimation but comes to similar figures as Ward for the Early – PPCS (A) – fusion technology he modelled.

Ward's results are for several different large plant design variants PPCS (A/B/C/D)[108]. Two variants are of interest here:

- Early Large – PPCS (A) sometimes known as DEMO1,
- Advanced Large – PPCS(C) sometimes called DEMO2.

The first (Early Large) is similar to the initial design of Flexi-DEMO[109] discussed above and the second (Advanced Large) includes all the upgraded technology of the later steady state version of Flexi-DEMO, with both improved materials, different blanket technology and higher power conversion efficiency.

Baseline overnight capital costs estimates[110] for a first commercial power plant (sized for 1,500 MWe) for these two options, together with key performance parameters are given in **Table 2** below (at 2020 economics and first commercial plant). Although there are many other differences in technology, one of the main drivers of reduced capital costs is the improve power conversion efficiency of the later Advanced technology design option. It also has higher power availability, reducing energy costs.

Table 2: Assumed parameters for Early and Advanced fusion power plants

Option	Power Output	Efficiency	Availability	Capital Cost	Target Date
Early	1.5 GWe	30%	54%	£8,346/kWe	2040
Advanced	1.5 GWe	42%	75%	£5,582/kWe	2060

The distribution of capital costs is shown in **Figure 4** below for the Early technology DEMO1 (sized for 500 MWe). This includes the initial cost of regularly changed reactor vessel and heating components. The largest element of cost is the magnet systems, followed by the reactor vessel, and then buildings and land. It is clear that improvements in the technology and production efficiency particularly for the magnet systems and vessel would have the largest effect on overnight capital costs.

Operating costs are important to fusion economics. Although the cost of deuterium fuel is very small, other operating costs are more significant. The fixed costs of staffing and support, and the variable costs of regularly replacing first wall, blanket and divertor components will be significant. The improved materials of the Advanced Large option should cut its variable operating costs. Estimates of fixed and variable operating costs for both options are in **Table 3** below.

Figure 4: Distribution of direct capital "overnight" costs for 500 MWe Early technology DEMO1[111]

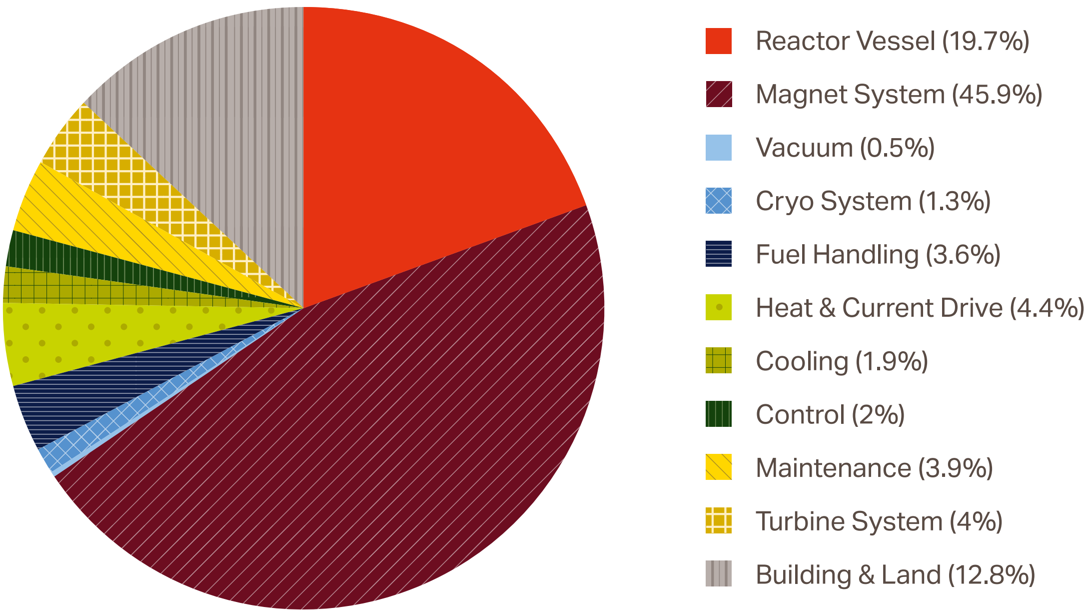


Table 3: Operating cost elements for large fusion power plants[112]

Option	Fixed	Variable
Early	£69/kWe pa	£16.5/MWh
Advanced	£69/kWe pa	£8/MWh

Risk and cost reduction potential

Construction costs are a key driver of fusion economics and hence competitiveness. These costs depends on the design and technology as well as construction location. There are two main options for reducing construction costs:

1. Economy of scale – larger units.
2. Economy of multiples – production learning for more units, each of smaller size.[113]

Economies of scale[114]

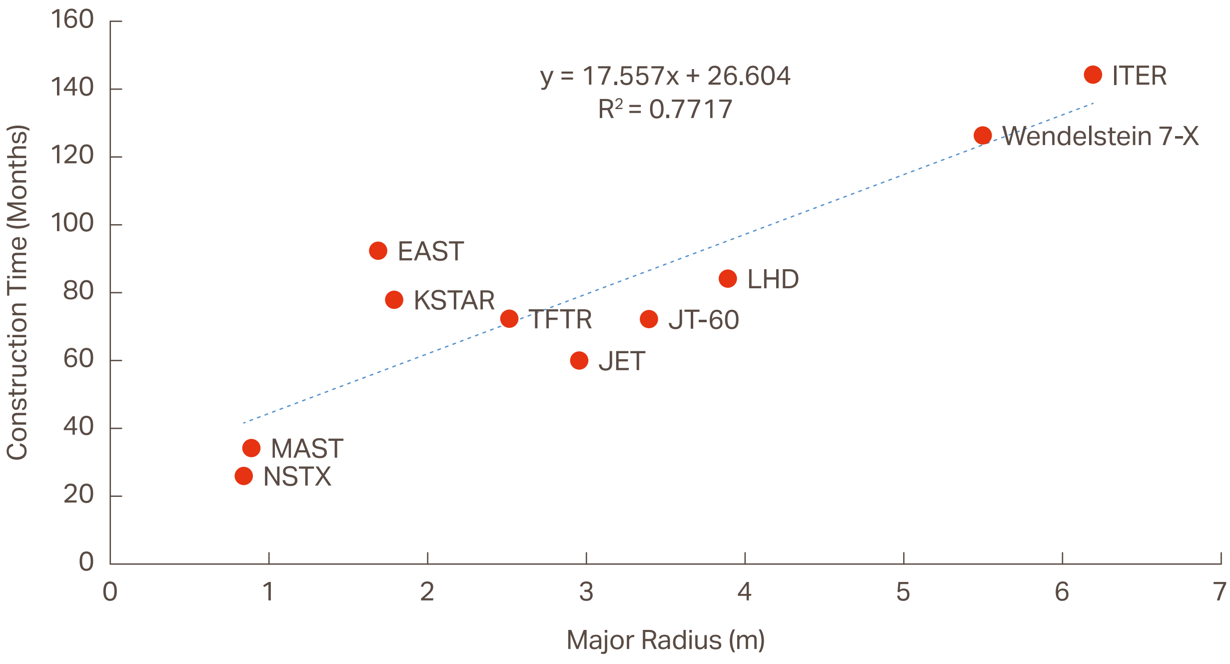
Over the last fifty years the size of complex infrastructure such as fossil fuel or nuclear power plant has increased substantially from a few hundred MWe to 1500 MWe and more. The reason behind these changes is because of the economy of scale, ie 'bigger is cheaper". The specific capital cost (ie per MWe capacity) and hence the energy costs (LCOE) of a power plant decreases when size increases.

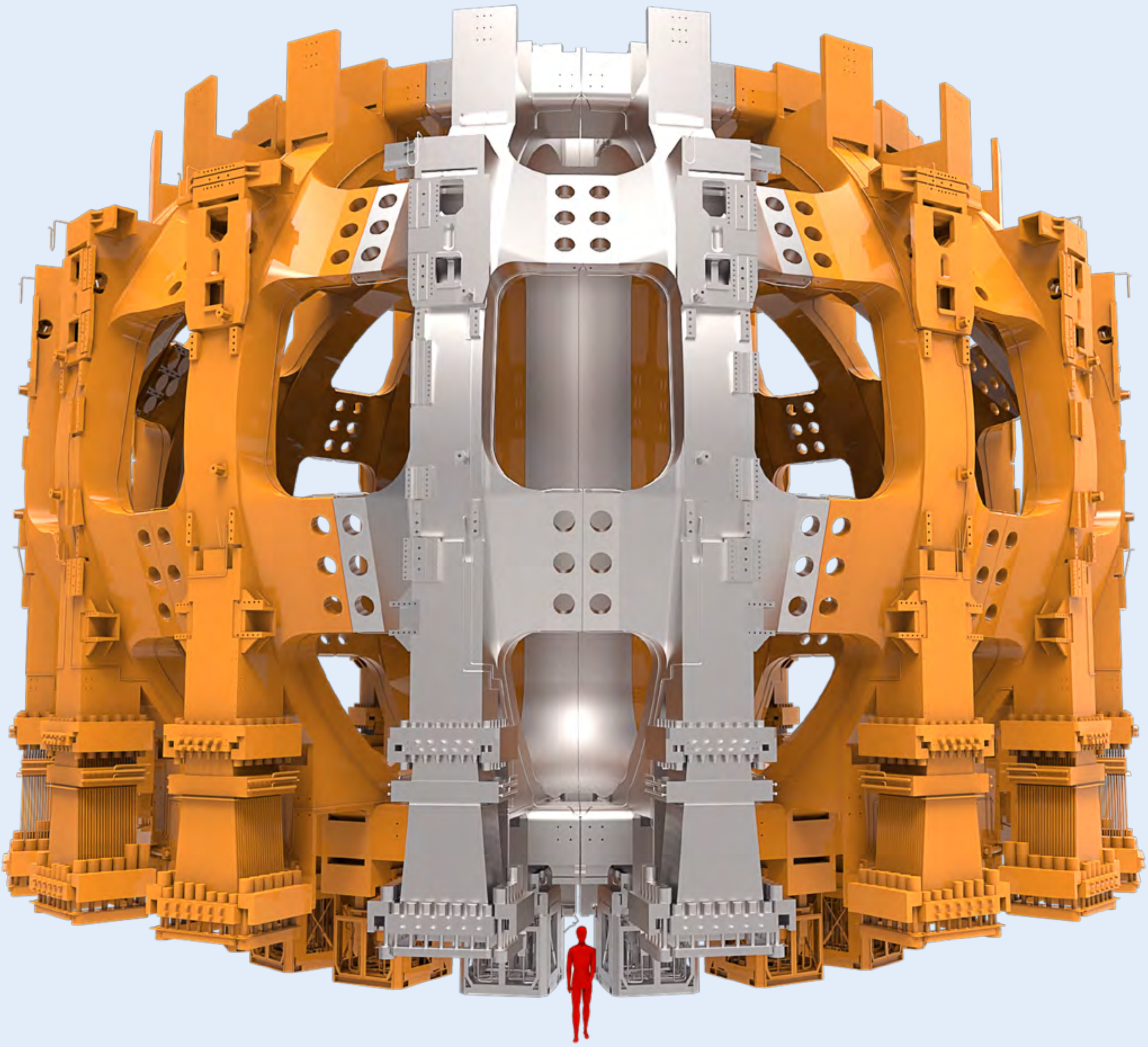
Capital cost reductions are due to several factors but this effect is born-out by experience. Similar principles are applied to the components of a fusion power system, taking into account technical and quality standards and the availability of similar production or construction capabilities.

Also, the larger the unit size, the greater the up-front investment required and therefore the funding requirement for each unit. Proposed fusion power plants are large (>1 GWe) and costly (~£5–10 billion) so they will be beyond the funding ability of both private developers and utilities and are likely to need government funding support. Large fusion plants will also take longer to construct, increasing the cost of capital. It is possible to examine this effect by plotting size (major radius) against construction time (also a proxy for cost).

The construction duration of large fusion experiments has been plotted against the major radius in **Figure 5**. Increasing size leads to an almost linear increase in construction duration. Though these are all experimental projects, it is likely that fusion power plant build schedules will exhibit a similar effect even if the actual build times may be shorter than an experimental equivalent sized project.

Figure 5: Fusion experiments' construction duration v Major radius[115]





Economy of multiples[116]

Lifecycle costs (construction, operations, decommissioning) also depend on how many similar (standard) units are built on the same site, or in the same country or globally.[117] When the same plant is delivered more than once, ideally several times, economy of multiples is achieved. Other things being equal, this reduces material, equipment, and labour costs. Economy of multiples in construction is related to the idea of mass production, first adopted in the automotive industry and later in other fields (eg aerospace, production of computers and smartphones). The economy of multiples is achieved because of two key factors: the learning process from series production, including the effect of investment in tools and techniques, and the economies of co-siting.

The replicated supply of plant components and the replicated construction and operation of the plant determines the pace of production learning. ‘Learning by doing’ reduces the cost of equipment, material and work and also reduces the construction schedule. The construction schedule is a critical economic and financial aspect of a power plant for two main reasons:

1. Fixed daily cost. On a power plant construction site, there are thousands of people working, often utilising expensive equipment. Consequently, each working day has relevant fixed costs.
2. The postponing of cash inflow. Postponing the cash inflow has two main negative effects. First, each extra year of construction increases the interest to be paid on the debt. Second, the present value of future cash flow decreases exponentially with time.

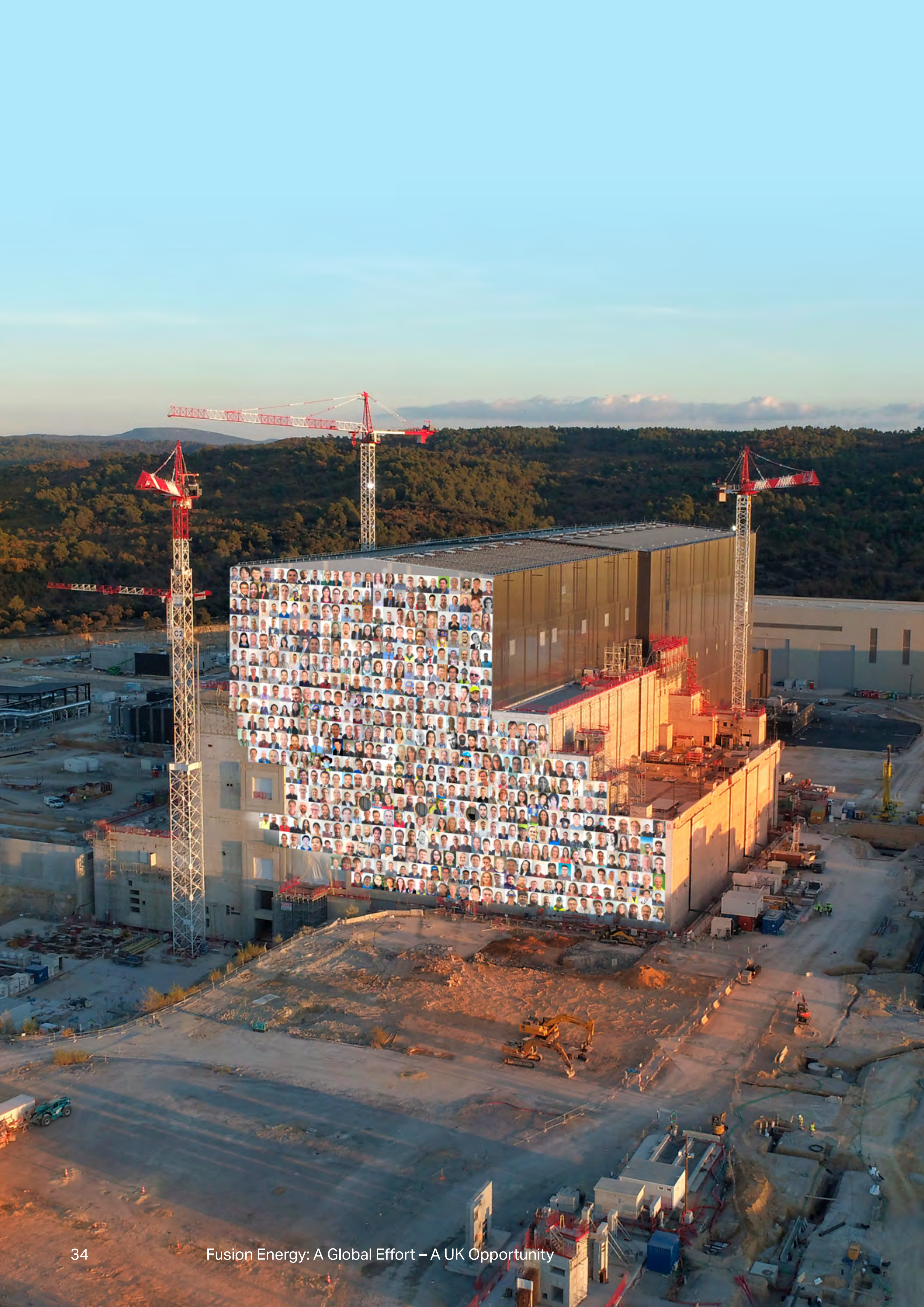
The unit cost of fusion reactors is expected to reduce for later versions of the same design of fusion reactor. Firstly, the one-off costs of the first of a kind (FOAK) should not be repeated. The learning process starts with the next of a kind (NOAK) and costs are progressively reduced with increased number produced.

These cost reductions can be considered in two categories:

1. Country-level – If a country plans to build a series of identical commercial fusion reactors there is scope for rapid learning and consequential cost reduction.
2. World-level – Costs are also reduced if they are built in different countries, though a lower rate than if supplied in and by a single country. This is because of the difficulty in translating learning between countries and differences in regulatory regimes and supply chains.

Co-siting economies[118]

Co-siting economies result from set-up activities related to siting (eg acquisition of land rights, connection to the transmission network), which have already been carried out, and by certain fixed indivisible costs which can be saved when installing the second and subsequent units. Therefore, the larger the number of co-sited units, the lower the unit’s total investment cost. Operational costs across fusion reactors would also be reduced due to sharing of personnel and spare parts across multiple units or the possibility of sharing the cost of upgrades. Analysis by the IAEA[119] suggests that, in the case of a fission nuclear reactor, identical units at the same site cost on average 15% less than a single unit. Siting and licensing costs, site labour and common facilities mostly drive such cost reduction. Therefore, two identical fission reactors at the same site are envisaged to cost less than double the single fission reactor’s cost. Further savings might be possible if the reactors share physical systems. This would be the same for fusion power plants.



Chapter 5
Financing fusion projects

This chapter includes an overview of:

- An explanation of the different types of financing
- The financing options at different stages of fusion development

Financing and economics are two different yet connected elements. In extreme simplification, an economic analysis deals with questions such as:

- What will the construction cost be?
- What are the key cost drivers?
- What electricity price will make this plant economically viable?

A financial analysis deals with questions such as:

- Who will pay for the construction of this plant?
- How much should the return be for each investor and over what time period?
- Who is responsible for a certain risk (eg cost overrun), and how is this risk remunerated?

This Chapter will focus on finance. It is fundamental to distinguish two key clusters of projects. Projects belonging to Phase 1 and 2, which are R&D projects vs projects in Phase 3 and 4, which are commercial infrastructure for electricity generation. Refer back to **Figure 3** in Chapter 3 for an explanation of these phases.

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[In early phases of development], there are R&D projects necessary to advance the science paving the way to commercial plants. It is useful to distinguish between government and private-led initiatives.

Financing R&D Projects (Phase 1 and 2 projects)

In these phases, there are R&D projects necessary to advance the science paving the way to commercial plants. It is useful to distinguish between government and private-led initiatives (the two broadest categories).

Government-led

Government-led projects can be led by a single county or shared between countries. Examples of single country projects include those at the UKAEA. Funding for the UK's domestic fusion programme comes mostly through direct grants from Government and via the Engineering and Physical Sciences Research Council (EPSRC). A notable exception in UKAEA is the operation of JET which is funded under a bilateral contract between the UK Atomic Energy Authority and the European Commission. Other projects are shared between the governments of several countries, like in the case of ITER. In this case: "During the construction phase of the project, Europe has responsibility for approximately 45.5 per cent of construction costs, whereas China, India, Japan, Korea, the Russian Federation and the United States will contribute approximately 9.1 per cent each".[120]

90% of these costs are cash, but "in kind," ie will deliver components and buildings directly to the ITER organisation. Countries are very keen to develop their owned content and future supply capability, ie increase the share of investment in its own country. This is beneficial since it provides jobs and industrial development. Therefore countries prefer to directly award contracts to their national industries instead of transferring funds to overseas organisations. This approach has some disadvantage from the "overall project perspective". For instance, contracts are not allocated on "best value for money" but based on political and local economic factors. Also, there are extra costs because of duplication of work or the extra complication of co-ordination between partners to realise an integrated solution.

Private sector-led

Increasingly, private organisations are investing in developing fusion technologies. A relevant UK case is Tokamak Energy. Based in Milton Park, in Oxfordshire, Tokamak Energy is a medium-sized private company, established in 2009, that aims to pioneer the development of commercial fusion energy based on spherical tokamaks with high temperature superconducting magnets (HTS). Tokamak Energy has built and successfully operated three prototype spherical tokamaks:

- Stage 1: A small prototype tokamak to demonstrate the concept (the ST25) – achieved 2013.
- Stage 2: A tokamak with exclusively high temperature superconducting (HTS) magnets (the ST25 HTS) – achieved 2015. "The ST25 tokamak is a new table-top tokamak, of major radius 25 cm and aspect ratio 2, and hence (marginally) a `spherical' tokamak (ST). It was designed specifically to test out the feasibility of a fully superconducting device made entirely from High-Temperature Superconductor (HTS) and hence be the first Tokamak to demonstrate the practicality of this new medium."[121]
- Stage 3: An aim to reach fusion temperatures of 100 million degrees in a compact tokamak (the ST40), followed by further development of the ST40 to produce high-density plasmas and get close to fusion energy gain conditions. 15 million degrees was achieved in 2018, 100 million is the goal in 2021 after a major upgrade of the ST40 allowing it to produce the world's highest magnetic field in a spherical tokamak.

The next goal for the business is to demonstrate a much larger system of HTS magnets in tokamak configuration by the end of 2021. This system is designed to replicate the conditions that the HTS material will see in a future fusion power plant. Tokamak Energy is aiming to have a pilot plant operating in the early 2030s. This progress leads to small fusion designs that Tokamak Energy and Commonwealth Fusion in the US are now pursuing.

The UK Government's Innovation and Science Seed Fund was the founding investor in Tokamak Energy in 2010, with a £25,000 pathfinder investment to support the founders in shaping their initial thinking about how a fusion neutron device might be developed commercially.[122]

The company is a spin-out from Culham Laboratory, employs 150 people (and is expanding) and has over 50 families of patent applications. The company has raised over £117m to date from private investors, including from[123]:

- David Harding, British billionaire and CEO of Winton;
- Dr Hans-Peter Wild a billionaire German-born Swiss entrepreneur and lawyer;
- L&G Capital, a British multinational financial services and asset management company;
- Rainbow Seed Fund an early-stage venture capital fund;
- Oxford Instruments plc, a United Kingdom manufacturing and research company that designs and manufactures tools and systems for industry and research.

While an organisation like ITER receives a constant and predictable annual cash flow from member states, companies like Tokamak Energy receive different amounts of money from different organisations without a predictable timeline. Some of these funds can also be research grants from public organisations, including £10 million from the UK Government as part of the Advanced Modular Reactor programme.[124]

Financing a commercial plant (Phase 3 and 4 projects)[125]

The financing of complex infrastructure such as fission and fusion plants can take different forms and involve different stakeholders.[126] A simplified summary of established financing models includes:

Government financing and interventions

Historically, governments around the world have invested public money in infrastructure, including power plants. Governments can be the sole owner of the infrastructure or own only a quota of it. Governments can also support the development of power plants without ownership. For instance, a government can lend money (at better rates than could be achieved in the commercial market) or provide a loan guarantee to investors (often private) in the projects. Government can also support a project by reducing investment risk, for instance, by providing some guarantee or support for the long term price of electricity. This price guarantee can take the form of a Contract for Difference where the government agrees to pay electricity (using future customers' money) for a fixed cost well above the market price. Governments can also use export credit agencies to support national companies developing business in other countries.

Private financing

In private financing, one or more private organisations raise funds for the project. A simple form of private finance is corporate finance, where an established organisation (often a utility) finance through a mix of debt and equity the planning and delivery of the project. The infrastructure will then belong to the company and will be registered on its balance sheet. The company's assets are the collateral against which the debt to finance the project is borrowed.


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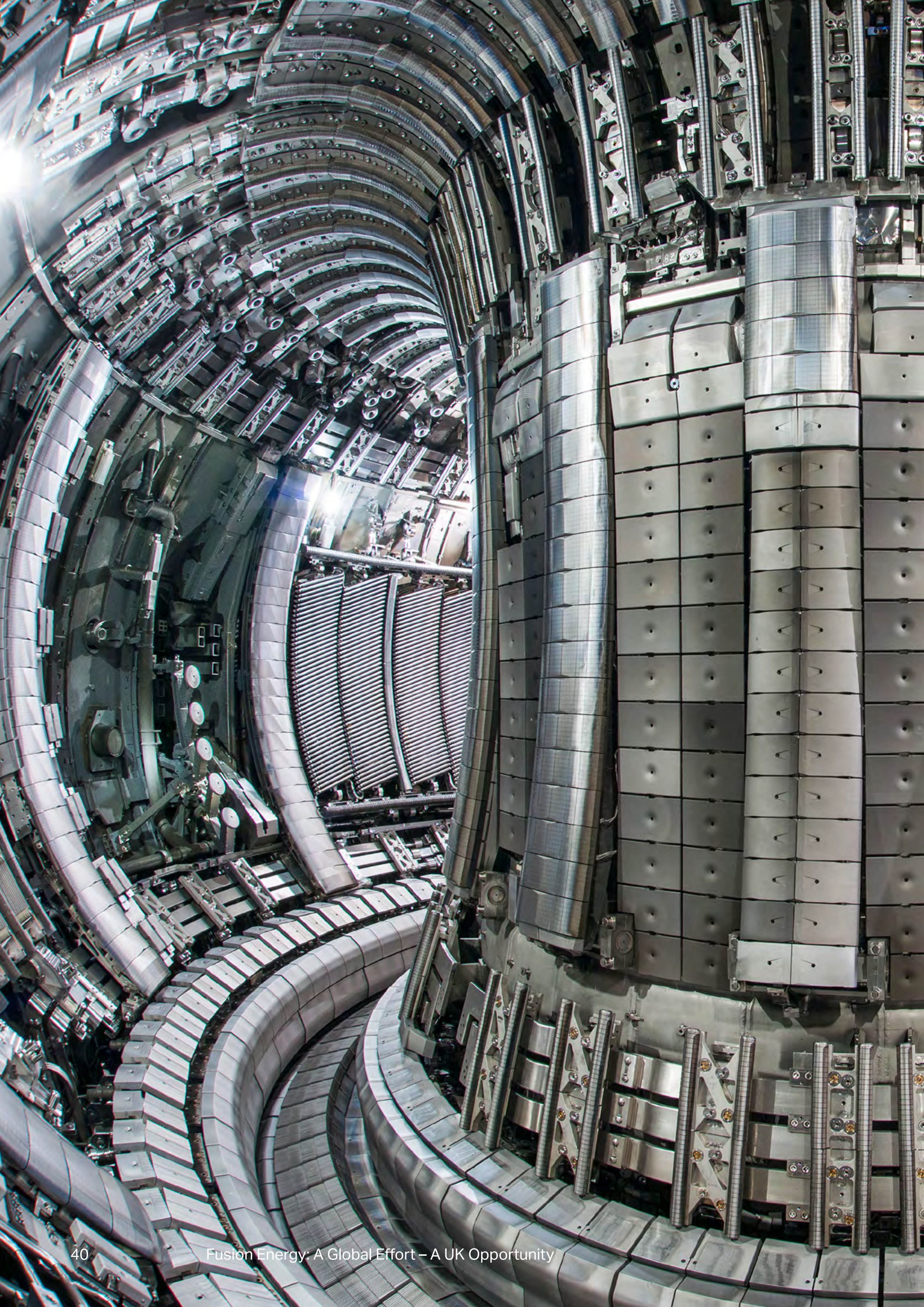
An alternative approach is project financing. Project financing is often compared to corporate finance.[127] In project financing, the debt is lent to an incorporated entity representing the project called a Special Purpose Vehicle (SPV), or Special Purpose Entity (SPE), ie "a ring-fenced organisation having limited predefined purposes and a legal personality".[128]

In corporate finance, lenders lend money to the project sponsors (eg the utility). This has at least two key implications. Firstly, corporate finance is a form of "on-balance sheet financing", and the project debt is considered in the sponsors' accounting statements. Lenders provide funds to the sponsors and not to the project directly. Project Financing is instead an "off-balance sheet financing" as the debt to finance the project is not revealed on the accounting statements of the sponsors.[129,130]

Secondly, in corporate finance, the financial risk is spread more widely between multiple projects, not allocated for each project independently. If the sponsor defaults, lenders would lose their capital. Sponsors are usually large utilities that have a range of different investments and assets. Their credit risk depends on these multiple activities, investments and contractual obligations. For example, a utility might own different power plant technologies, such as coal, nuclear, CCGT, etc. In the case of liquidation of the sponsor, lenders can have recourse to its assets. Therefore, corporate finance is often "collateralised" that is to say, the debt is backed by collaterals provided by the borrower or sponsor.[131]

Lastly, an approach that is becoming increasingly popular is vendor financing, where the company "selling the power plant" (often a government-owned company) is also providing the financial resources to build it. Often these plants are built in country A by a large government-owned company from country B. Country A can provide some form of long term guarantee for the electricity price, making the investment attractive for country B.



Chapter 6
Economic modelling of fusion costs

This chapter includes:

- Economic modelling of three illustrative tokamak technology options
- Projected future cost reduction through technological learning
- Analysis of the main cost drivers for fusion energy systems
- Estimates of cost targets for fusion to become commercially competitive

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Smaller units can compensate for their diseconomies of scale through increased production learning and from their potentially shorter build schedule.

In this Chapter, a range of indicative costs of electricity from fusion are calculated based on data from previously published studies and making a number of different assumptions. Given the limited data available, and the inherent uncertainty in calculating the future costs of immature technologies, the numbers should be taken as illustrative. The actual costs of fusion energy systems will only become clear through an initial programme of development and deployment.

Scenario analysis

In modelling electricity costs for different scenarios, the following factors are considered:

- How production methods could reduce costs over a programme of a standard design, built sequentially and operated in the same manner.
- Sensitivity of energy costs economic and performance factors.
- Improvements in fusion technology and of different designs concepts.

Figure 6 shows the effect that the planned improvements in the technology of large fusion power plants has in reducing capital costs through better power availability and better efficiency. The first standardised commercial unit is called the Next of a Kind (NOAK). It does not have the one-off design, development and regulatory costs of the First of a Kind (FOAK) plant. Cost reduction through production learning is achieved through the standardisation of design and supply chain and progressive improvement in production techniques as manufacturing methods are refined. Production learning is a widespread and key strategy of cost reduction in manufacturing. Based on energy sector data and similar to previous estimates[132], we use a production learning rate of 10%. This has the effect of a 30% capital cost reduction for the 10th unit. For the small design with its larger numbers (75 units) to provide the same level of power capacity as the larger design the cost reduction is 48%.

Production learning is important in reducing the effect of the initially very high capital costs. This is particularly the case for small fusion reactors where costs will initially be inevitably higher. Both the higher volumes for the same power capacity and the greater ability to use series factory manufacturing for the smaller components will have the most significant effects. Even so, it appears that the mature small unit capital costs per kWe will be higher than the capital costs per kWe of their larger counterparts.

Capital cost is a key cost driver (see the sensitivity analysis in **Figure 3**); therefore, its reduction is broadly reflected at the LCOE level. These graphs show that only through a robust learning process can fusion technologies become competitive with other low-carbon infrastructure such as modern light water reactors. Therefore, investors and policy makers need to approach nuclear fusion not at the project level (ie the single reactor unit) but as a programme (ie the construction of a series of units). This implies establishing governance at the programme level, establishing practices to learn across projects, benchmarking across projects, etc.[133]

Figure 6: Effect of technology, production learning and size on overnight capital cost[134]

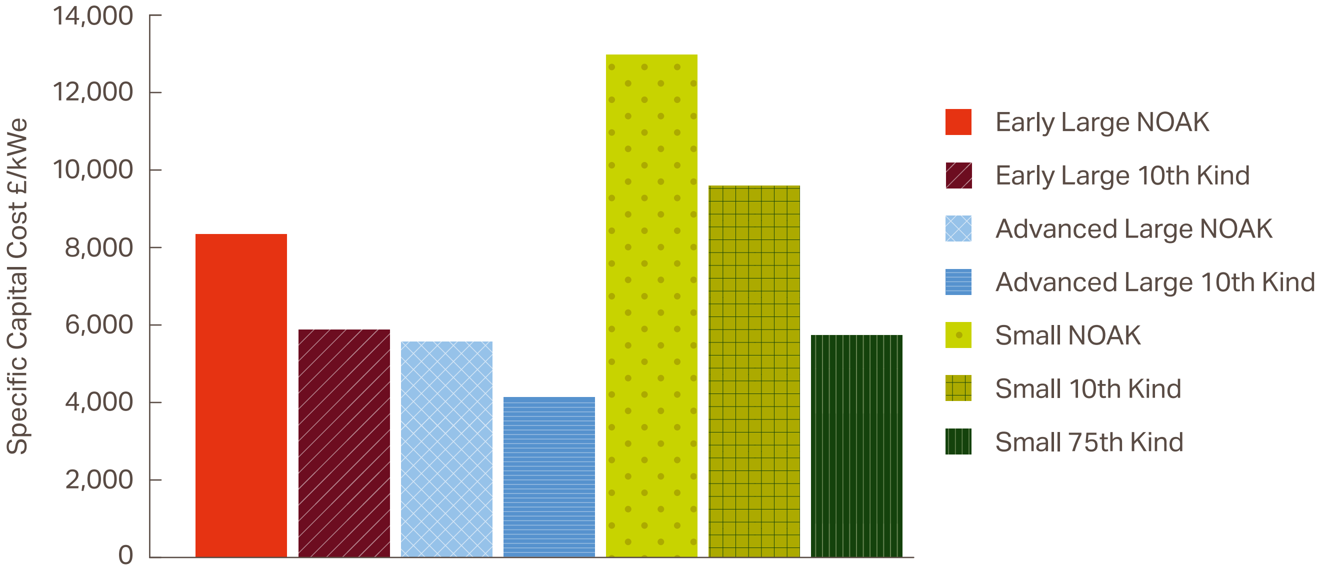


Figure 7 summarises the medium long-term cost for mature fusion power plants. Depending on the discount rate, the LCOE of the 10th unit, Early Large, can range between £114/MWh at 5% and £184/MWh at 9%. This value makes the technology uncompetitive today with other low-carbon options available in the UK, ie wind and LWR (fission) reactors. The reason for this behaviour is the combination of a relatively high construction cost (£5,887/kWe) and a low capacity factor (56%). Considering an improved design – Advanced Large – the construction cost decreases to £4,135/kWe and the capacity factor increases to (75%). These two effects improve the fusion economics, decreasing the LCOE into the range £60 to £97/MWh.

As this is the 10th unit, it might be relevant to ask the question: What would be the cost of getting there?

Considering that the first Advanced Large design has a specific capital cost of £5,582/kWe and the 10th unit has a capital cost of £4,135/kWe, we can say an average of £4,800/kWe for the 10 units. Considering the size of 1,500 MWe for each plant, the investment for this programme of construction is in the ballpark of £72 billion (for 15 GWe installed).

Smaller units can compensate for their diseconomies of scale through increased production learning and from their potentially shorter build schedule. Considering the Advanced Small technology option, the energy cost of 75 units is in the region of £69–£99/MWh – a range that is comparable to 10 units of Advanced Large and also the energy cost of LWR fission reactors.[135]

This is the 75th unit cost, therefore it might be relevant to ask the question: What is the cost to get there?"

Considering the first commercial unit has a capital cost of £10,936/KWe and the 75th unit £4,822/kWe, we can say an average of £7,800/kWe for the 75 units. Considering small fusion plants of 200 MWe, the investment for this programme of construction is £117 billion (for 15 GWe installed), hence requiring more funding than Advanced Large programme, though with a capital costs £1 billion per unit rather than £7 billion, making it more suitable for private investment once proven as a project.

Figure 7: Medium Long term LCOE for fusion power plants for different discount rates[134]

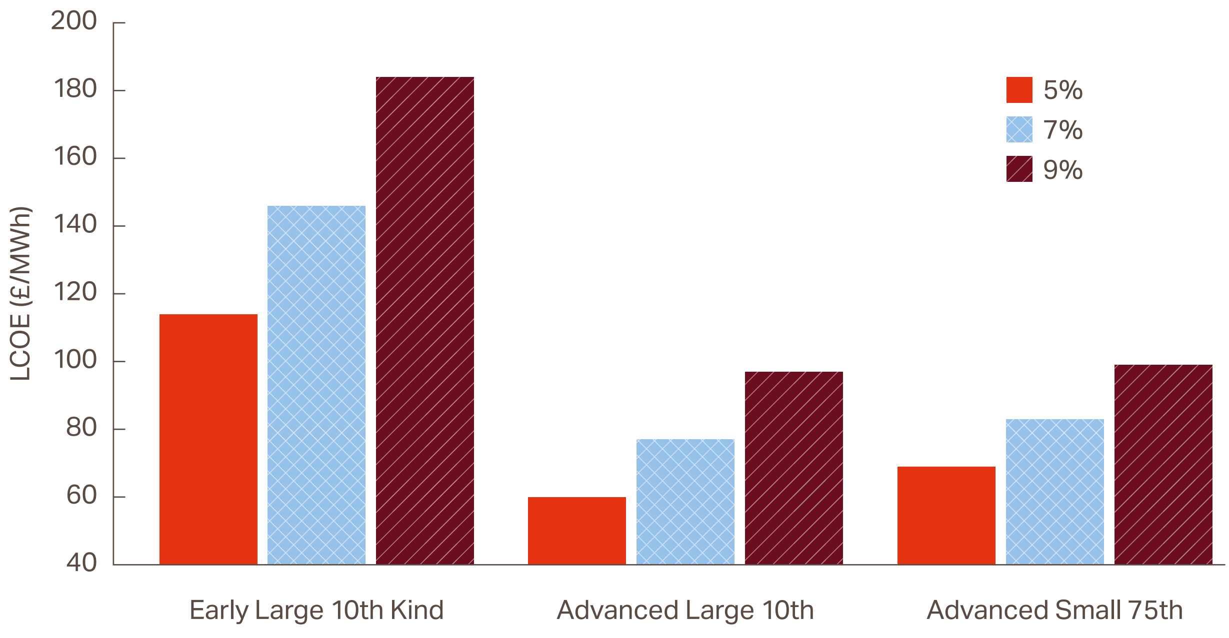
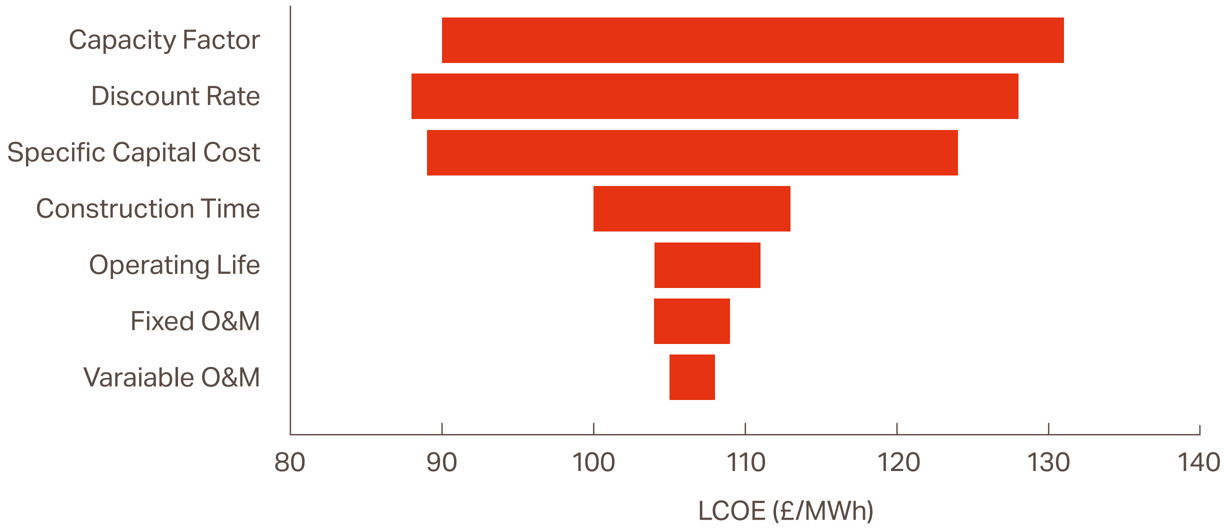


Figure 8 provides a sensitivity analysis using, as a reference case, the 10th unit 'Advanced Large' for a 7% discount rate. The results indicate that capacity factor, discount rate and capital cost are the key cost drivers for the LCOE. This result is unsurprising and similar to what is obtained for other low-carbon technologies, such as wind farms or large pressurised water reactors.

- The quantity of electricity produced and hence revenue is directly proportional to the capacity factor. If the capacity factor doubles, the electricity produced doubles. The majority of the cost are fixed (Fixed O&M) or sunk (Capital cost). The energy cost is almost halved. Consequently, fusion devices need to be designed considering a high capacity factor, ie short and infrequent stops of the plant for any planned or unplanned outage.
- The financing discount rate is relevant because these plants are extremely capital intensive, have long construction cost and long operating lifetimes. Consequently, the discussion of their financing (ie who is paying for them and at what rate?) should be a key topic of discussion for policy and decision-makers.
- Like other low-carbon plants, fusion plants are expensive to build and, hopefully, relatively cheap to operate, making capital cost a key cost driver. The consequence is that project and programme management have paramount importance.

Topics such as modularisation, constructability, rework reduction etc., need to be carefully studied in this setting. Also, technical and manufacturing ways of reducing capital cost more rapidly would have a significant effect. For example, more rapid reduction in the cost of magnets for the Small design with its novel rare earth barium copper oxide (REBCO) high temperature superconducting coils[136] with its scope for much higher current density and production cost improvements would be important. For a higher production learning rate of 15%, which is typical of such a new technology, for the magnet system, mature capital cost could be as low as £3,200/kWe and energy cost reduced to £63/MWh (for 7% financing).

Figure 8: Sensitivity analysis



Energy cost comparison

Renewable energy costs have fallen substantially during the last 10 years. Many sources forecast that they will continue to fall and by 2040 will have the lowest LCOE of any low-carbon energy supply. As a result they will become the dominant means of electricity supply in many countries and set the market price for electricity. Renewable energy cost forecasts for 2040 for Western Europe[137] (global values are in general lower than these), are given in **Table 4** below.

UK renewable energy studies show that solar shares will continue to be low because of the low level of solar input to the UK. Also, the level of balancing systems is lowest when the solar share is about 20%. Wind energy availabilities are much higher. Most of the wind capacity growth will be offshore to reduce public concern about the intrusion of onshore wind turbines and to be able to meet the large forecast capacity requirement. It seems likely that by 2050 the offshore/onshore wind share might reach as high as 70%/30%. Using the cost values from above, the blended renewable energy cost would then be $47/MWh, or £34/MWh (at purchasing power parity exchange rates).

As explained in the first chapter of this report, wind and solar power are by their nature intermittent. Both providing diversity of renewable supplies (solar, onshore, offshore wind etc.) and distributing them across the whole country and its surrounding waters have a positive effect in smoothing renewable supplies. Nevertheless, to ensure supply reliability there remains the need for flexible supplies and/or energy storage to complement these variable renewable supplies. This need for balancing supplies increases with renewable supply share and it becomes more important when the variable renewable share exceeds 50%. The additional system costs for complementary or balancing supplies need to be added to renewable LCOE values, recognising that solar and wind energy are likely to supply in excess of 60% of UK electricity by 2050.

Studies by OECD for countries across Europe and for the US estimate the add-on system costs for different levels of renewable penetration (see **Figure 9**). System costs include:

- Profile costs (mis-timing of supply),
- Connection costs (additional cost of bringing power to the grid),
- Balancing costs (stand-by supply or energy storage),
- Grid costs (transporting highly variable energy flows between regions of source and demand).

The additional system costs are ~ $30/MWh (£21/MWh) for 50% variable renewable share and $50/MWh (£36/MWh) for a higher 75% production share.

Table 4: Forecast costs of renewable power

Renewable Energy	Specific Capital Cost Per Kwe	LCOE per MWh
Solar	$440	$30
Onshore Wind	$1,380	$45
Offshore Wind	$1,820	$35

Analysis of the use of energy storage to balance a highly renewable energy system[139] for the UK considered two main categories of system costs:

- Back-up (similar to Balancing costs in **Figure 9**, but in this case cost of storing and supplying from energy storage),
- Overcapacity (similar to Profile costs in **Figure 9**).

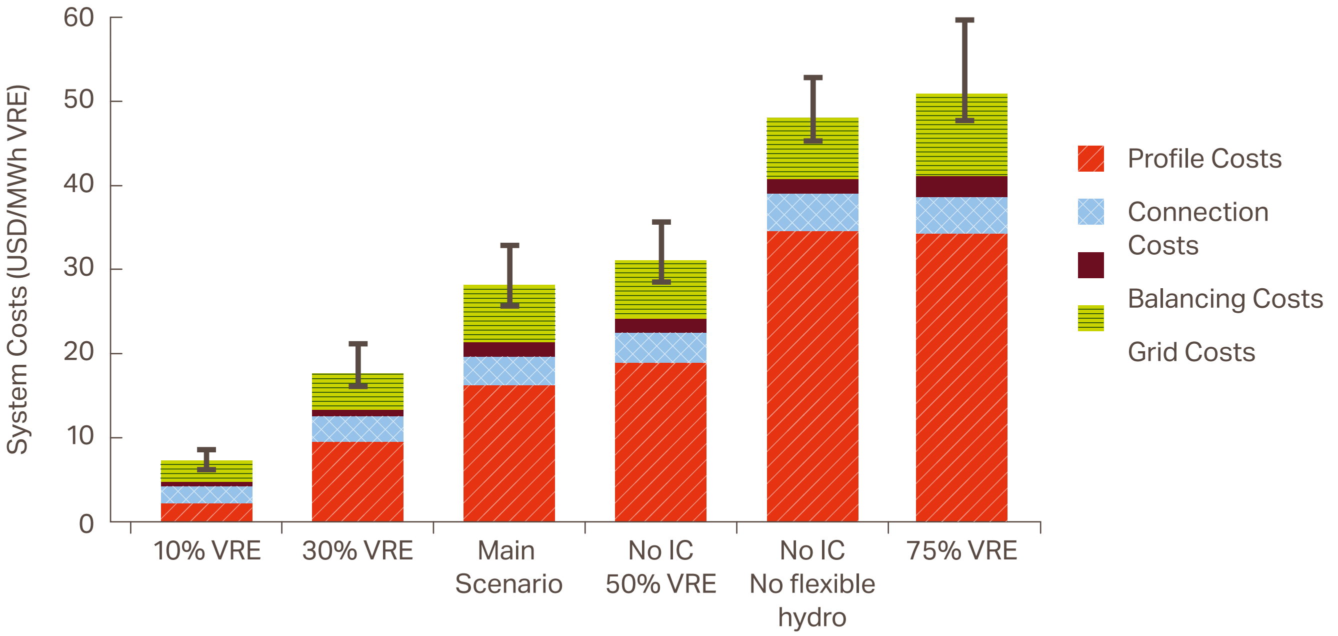
The analysis was based on an hour-by-hour analysis of expected demand in 2050 and 37 years of weather (1980–2016). It found that several storage technologies would be required to meet both the large power and the large storage capacity needs:

- Batteries for short-term (up to one day) energy storage, plus
- Physical and/or chemical systems, such as hydrogen, for longer-term (weeks/months/years) of energy storage.[140]

Whole system costs for energy storage are uncertain because of the lack of experience in deploying many of these technologies at scale.

Costs are strongly dependent on the technology used, together with its maturity and scale. In this study[141] of a 70% variable renewable energy system the extra costs were found to be between £21/MWh ($30/MWh) and £42/MWh ($60/MWh), but additional system costs could be as high as £63/MWh (90/MWh). Using the middle estimate from above and recognising that they have a different composition to the OECD study, whole system costs with energy storage are similar to the OECD estimate for 75% variable renewable energy ($50/MWh). This would increase the whole system energy costs for renewables from: £33/MWh to £70/MWh with a range of cost uncertainty from £54/MWh to £99/MWh. These future energy costs provide the competitiveness test for fusion beyond 2040. It is clear from **Figure 3** that only fusion power plants with high power availability, high efficiency, low capital cost from series production learning and with relatively low cost funding would be economic. Only mature Advanced Large and perhaps Small Advanced designs – if magnet costs can be reduced more quickly – have the potential to deliver future energy costs close to, or below £70/MWh which would make them competitive beyond 2040 with the expected dispatchable low-carbon energy. Both of these Large and Small fusion power plant designs depend on materials and physics technology that may not be available until after 2050.

Figure 9: Systems costs of variable renewable energy technologies[138]



Conclusions

ITER should demonstrate feasibility (high fusion gain, etc.), and thereby provide some useful engineering design signals by the middle of the 2030s, for the fusion power plants that follow. Some key technology and design integration issues for these power plants will still be outstanding and be addressed by parallel development projects. Estimates of costs for fusion energy at this stage of development are inevitably uncertain.

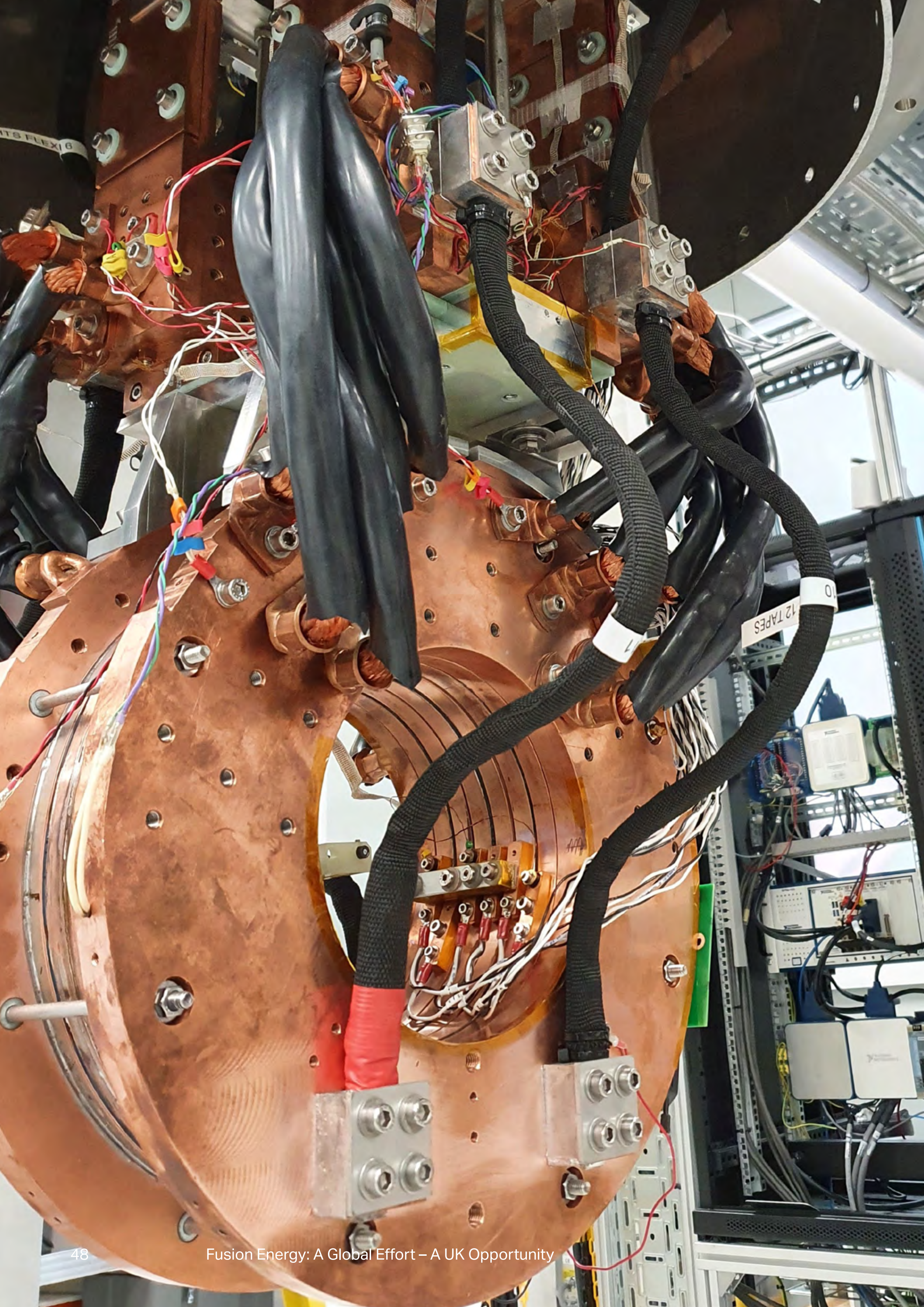
Without a breakthrough in capital costs, it may be difficult for Early Large fusion designs to be competitive, even with the benefits of a large programme of build and production learning. Modelling suggests these early fusion energy costs may be greater than £100/MWh – due to the low power availability from both pulsed operation and frequent replacement of vessel components, and the low efficiency power cycles of these designs.

Current analyses identify some key drivers of cost and competitiveness:

- Capital costs of fusion are currently high, with the core device costs – magnets, vessel & divertor and blanket – being more than 66% of direct costs and almost 50% of total costs. Reducing the cost of these key components by innovation in either design or manufacture, and by production learning will have the most effect in making fusion competitive;
- Though fuel costs are low, other O&M costs are significant – particularly the cost of replacing life-limited vessel and blanket components;
- Reducing the amount of power to maintain the plasma and to run the reactor could significantly increase net output and reduce fusion energy costs;
- Higher power availability or capacity factor and higher power conversion efficiency will directly improve fusion energy costs;
- Shorter build times and lower financing charges improve fusion energy costs and hence competitiveness.

More advanced steady-state fusion designs, available perhaps a decade later, offer the possibility of competitive energy costs based on repeated production of standard systems, with lower financing costs. They depend on better materials technology and improved operating characteristics that require separate development efforts in addition to those linked to ITER.

Small fusion power plants may have the potential to offer a faster route to market for fusion power, but initially they could have higher cost barriers because of the dis-economics of their smaller scale. These effects can in principle be offset both by the economics of multiples and by shorter build times for these smaller power plant.


12 TAPES

Chapter 7
The market for fusion

This chapter includes:

- An estimate of the potential global market for fusion electricity in 2040–2060
- Alternative non-electricity markets for fusion

Fusion, with its high capital costs and low operating costs, has similar economic characteristics to fission. Both are best suited to constant operation – something once called baseload operation – maximising the power produced and the revenue generated. As well as electricity generation, there are other potential uses of fusion energy such as district and industrial heating, desalination and perhaps hydrogen production by electrolysis. Some innovative companies also use their expertise in fusion and apply it in non-energy markets (see page 52 – More than energy).

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The provision of both heat and electricity with the ability to switch between different demands would help fusion integrate with the fluctuating demand of an energy system dominated by intermittent renewables.

Electricity

The largest market for fusion will be the generation of electricity. Global electrical demand is large and as economies grow and as low-carbon electricity replaces fossil fuels, the global demand for electricity will increase even taking into account energy saving from about 27,000 TWh to 40,000 TWh in 2040.[142] During this period the fossil fuelled generation by 2050 that currently provides 59% of electricity will be largely eliminated. Fusion, like fission, as a dispatchable source of zero-carbon energy has a huge potential market opportunity but it needs to be competitive on price.

In the UK, nuclear fission currently provides approximately 17% of UK electricity and in the future this share of the market is likely to continue, even with a largely renewable electricity system as long as fission energy costs are similar to the whole system cost of renewables. The case for nuclear fusion is similar with the added benefits of almost limitless fuel supply and much lower waste volumes.

The potential global electricity market for fusion can be estimated from IEA World Energy Outlook forecasts[143] for 2040, an average of 600 GW per annum of new electricity generation will be required in their Sustainable Development Scenario.

New capacity is dominated by solar and wind both because of their low cost and hence popularity, but also because of their low capacity factors which means that a larger installed capacity is necessary to meet demand. In addition to solar and wind, further new capacity of 350 GW per annum is required. If the UK's Net Zero obligations are to be realised, this needs to be met by low or zero carbon energy – which includes: nuclear, hydro, bioenergy, geothermal, concentrated solar power, marine energy and battery storage. These low-carbon sources represent the potential market. Assuming this level of new capacity continues in the following period 2040–2060 fusion will compete in a 140 GW per annum market.

Table 5 shows how this potential market is shared across the main regions of the world. If fusion were to take 25% of this market this would be 700 GW over the 20 years to 2060 – which is more than the current global fission capacity. The largest market is Asia Pacific with similar sizes of market in the America and Europe, Middle East and African regions – each representing a capital spend of at least £40 billion per annum.

Table 5: Potential future market of fusion

	Low-Carbon Market	20 Years & pa	25% Fusion Share	20 Years & pa
Total	2,2823 GW	140 GW pa	700 GW	35 GW pa
Americas	710 GW	35 GW	177 GW	8 GW pa
EMEA	821 GW	41 GW	205 GW	10 GW pa
Asia Pacific	1,292 GW	64 GW	323 GW	16 GW pa

Heat, hydrogen, desalination

Plans for Net Zero energy systems will create large demand for energy carriers such as hydrogen and ammonia to replace oil & gas, also as means of storing energy and making renewable energy systems reliable. Aurora Energy Research have estimated that the market for hydrogen in Europe alone could be worth 120 billion euros by 2050.[144]

Producing hydrogen by electrolysis might provide another market for fusion. Electrolysis of hydrogen from water has inefficiencies as does its reconversion to useful energy. The round trip efficiency of such a system is in the range 30–42% with the higher figure depending on the better conversion efficiency of fuels cells. Because this process of electrolysis and conversion is less than 100% efficient, it requires the cheapest form of zero-carbon electricity. In the future, this is likely to be from renewables, rather than higher cost fusion.

Fusion, like fission, produces large amounts of heat and this can be used to meet other energy demand such as district heating using low temperature steam, or industrial heat using higher temperature heat for chemical processes, desalination or perhaps the direct production of hydrogen by splitting water. The scale of these demands could be large but are determined by infrastructure and by relative economics. Given the similarities of the economics and scale of fusion and fission the recent policy briefing[145] by the Royal Society (and the earlier work by UK ETI[146]) provides relevant information for fusion.

The provision of both heat and electricity with the ability to switch between different demands would help fusion integrate with the fluctuating demand of an energy system dominated by intermittent renewables. Co-generation for district heating could be readily incorporated into the power conversion system of fusion power plants. The question is more about the distribution of this heat either to homes or to more concentrated industrial sites. District heating is a feature of some Northern countries that have provided city-wide networks for heat transport.[146]

In most countries in the world including the UK, the installation of such networks in and between cities would be costly and would be very difficult where housing densities are high. Industrial sites would be simpler to access for district heating. This includes desalination which requires both electricity and heat. Detailed economic studies are required to determine whether fusion would be economic for this application.

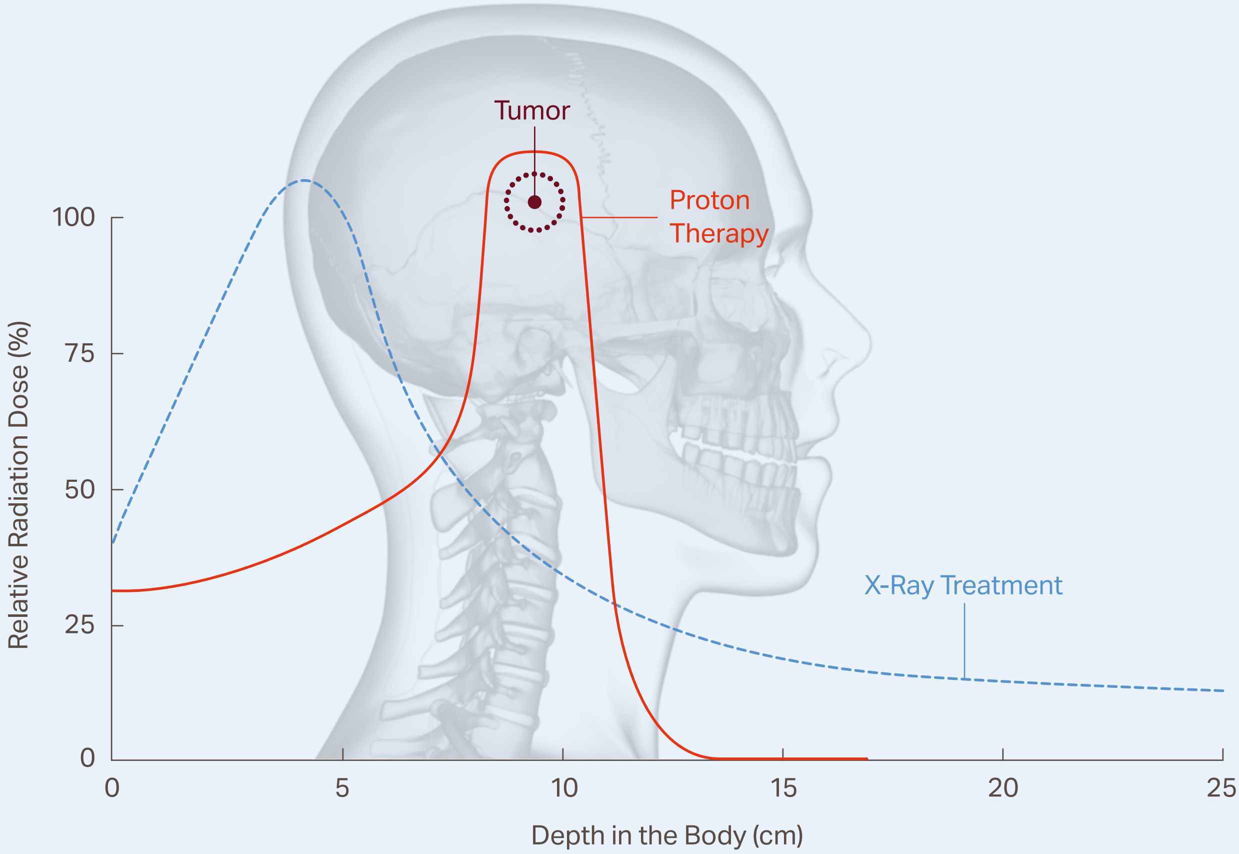
Like fission, fusion could in principle provide high temperature heat: 500–900 C. This would be attractive for several industrial processes that depend on high temperature heating. For example, the efficient production of hydrogen requires temperatures between 600–1000 C – employing either high temperature electrolysis, or advanced steam reforming of methane, or direct splitting using the sulphur-iodine process. Initially fusion power plants will be materials limited to lower temperatures making these high temperature industrial processes infeasible. Advanced fusion materials are targeted to be available beyond 2060 and these may provide the opportunity to address such industrial processes.

TAE Technologies[148]

TAE Technologies (formerly Tri Alpha Energy) is one of the many start-up companies who have ambitions of an accelerated path to developing a commercial fusion reactor. However, even if these ambitions can be realised a decade or more is still a long time to be an R&D company that does not generate revenue.

This is why TAE use their expertise to develop products and services for other complementary markets, including:

- Power management systems, both for electric vehicles and for local electricity grids.
- TAE's first subsidiary, TAE Life Sciences, employs compact and flexible particle accelerators for treating cancers. Boron neutron capture therapy, like proton therapy uses the physics concept of the Bragg Peak, which allows for more precise targeting of tumours, with less damage to healthy cells, than traditional radiotherapy.



Chapter 8
Fusion intellectual property

This chapter includes:

- An exploration of global and UK-based fusion IP

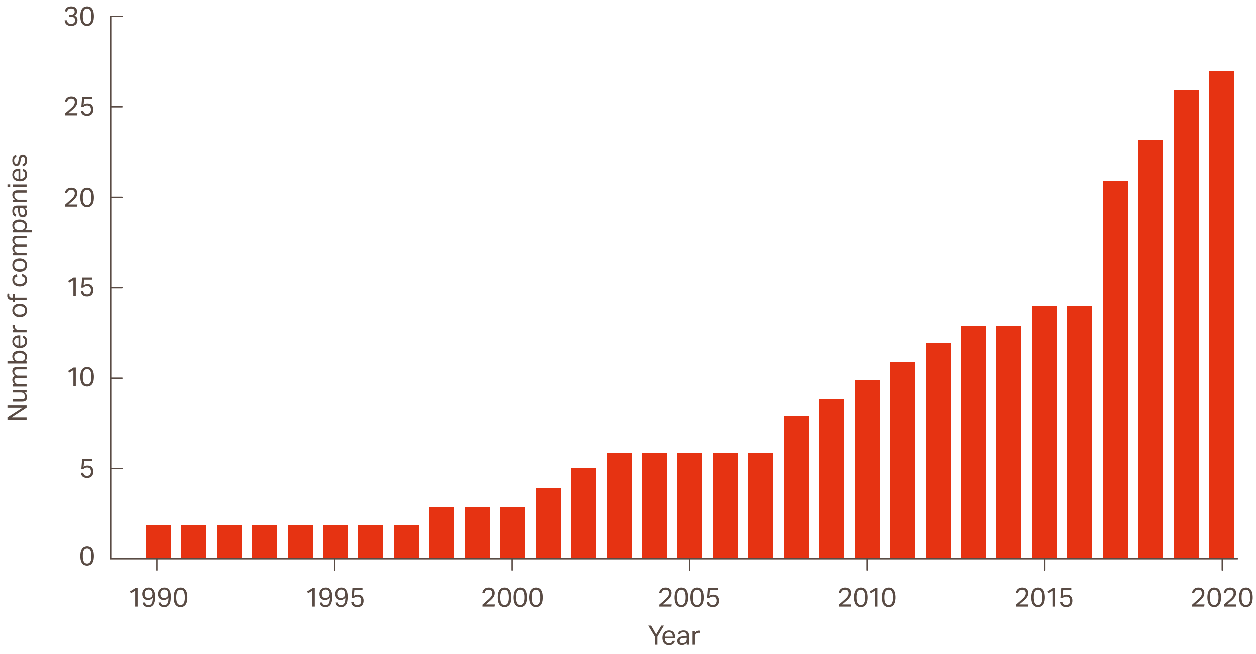
The global intellectual property (IP) landscape

The Fusion Energy Base website lists 90 research organisations involved in the development of fusion energy.[149] These are primarily national laboratories, funding bodies, and universities. Notable examples include the US Department of Energy and the Japan Atomic Energy Agency.

The high level of investment required to conduct research into fusion, combined with the long time period before any potential return, has meant that most historical investment has been via national governments. However, this is beginning to change.

For decades the preserve of national laboratories, private fusion companies are now proliferating. The Fusion Energy Base website lists 27 private companies whose primary business is the development of a novel fusion reactor for electricity production.

Figure 10: Number of private companies pursuing fusion energy by year of their creation[152]



Most of these have come into existence in the last 12 years. Their database also lists 68 investors in fusion energy, which includes high wealth individuals, investment firms, sovereign wealth funds, and public funding bodies (eg ARPA-E in the USA). Investment in the sector has been growing for some years. The New York Times has reported that total private investment in fusion is approaching $2 billion[150], including at least $750 million in TAE Technologies (see page 52 – More than energy) and $200 million in Commonwealth Fusion Systems.[151]

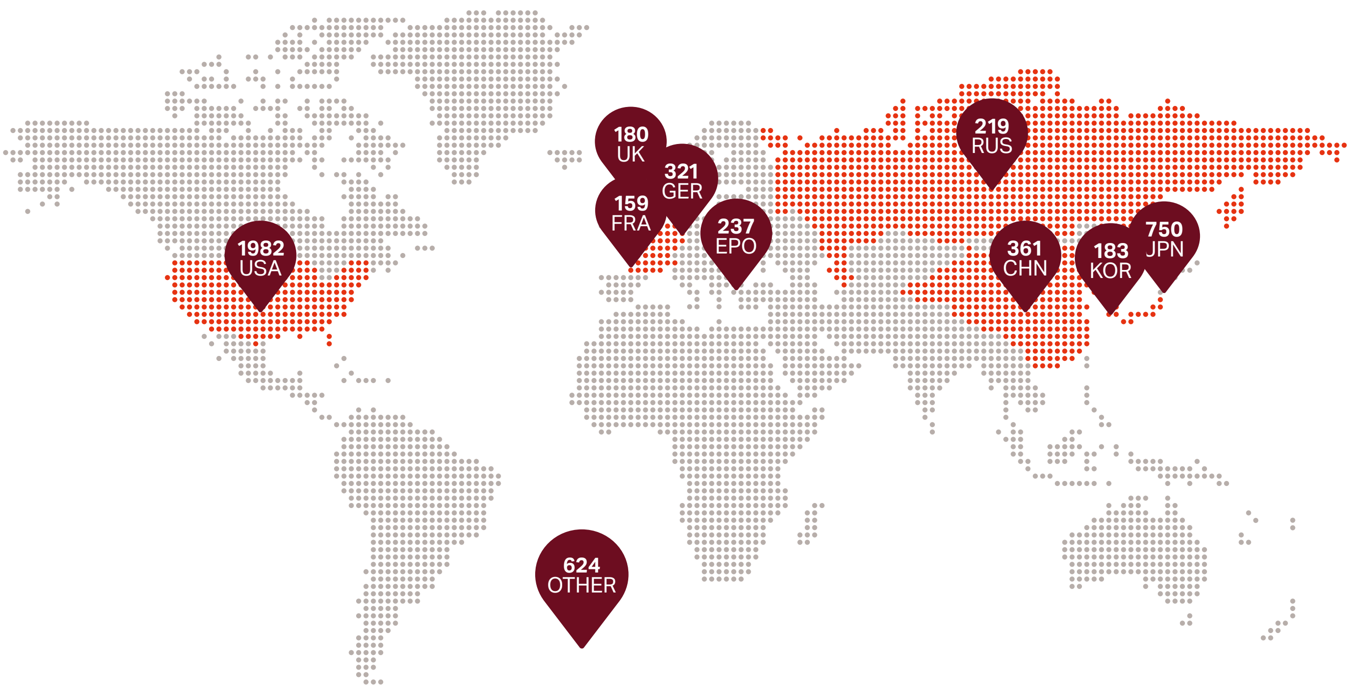
This rise in private sector investment has contributed to a broader steady rise in the number of patents filed per year. In a 2016 report, iRunway conducted an analysis of the global fusion energy landscape. They found 3,052 patents granted relating to nuclear fusion, with a majority (1,982) being owned by US-based individuals and organisations.[153] The US Department of Energy was found to be the leading patent holder in the world.

To get more up-to-date information, a patent search was conducted for this report using Patent Scope, Espacenet, and Google Patents. Since the beginning of 2016, there have been over 1900 patents filed globally related to fusion reactors. Stand-out developments include:

- 40 patents have been filed in the Chinese Patent Office by the Laser Fusion Research Centre, which is part of the China Academy of Engineering and Physics.
- 22 patents have been filed by TAE Technologies in the United States Patent and Trademark Office.

A research paper published in Fusion Engineering and Design in 2021 analysed the patents filed by Fusion Industry Association members (private fusion companies) by year and found a rapid rise in recent years. In 2012 they found just two patents filed, but this rose to a peak of 34 in 2019.[155]

Figure 11: Countries owning the most number of IP assets in fusion technology[154]



The UK IP landscape

The Government, via the UKAEA, funds and co-ordinates the vast majority of activities relating to fusion in the UK. A BEIS commissioned report[156] published in 2020 and summarised on the next page of this report found that "there were 40 patents citing Culham publications in 2013–19, including medical applications, automobile, materials and fusion. Of these, Tokamak Energy patents accounted for 25% of total cited patents (or 10 patents) in the period." The report also looked into the wider value of the UKAEA R&D programme as a whole. The findings are summarised on page 56 – Impact of UKAEA R&D.

Tokamak Energy: At the time of writing, Tokamak Energy hold 56 patents, most of which (38) relate to high temperature superconducting magnets, with applications including those broader than fusion energy. Additional patents relate to neutron shielding, plasma control, and diverters.[157]

First Light Fusion spun out from the University of Oxford in 2011, exploring different approaches to delivering fusion power. Their principal funders, IP Group and Oxford Science and Innovation, hold equity stakes in the business. They hold nine patents and 160 trade secrets.[158] Their business model is based around the development of targets for their projectile-based inertial fusion concept, so they would seek to collaborate on other parts of the system in the event the company expands in scope to the point of developing a working prototype reactor or power plant.

More than patents

The 2016 iRunway study found that 60% of patents relating to magnetic-confinement thermal fusion had expired. This points to the long timescales involved in the development of fusion energy and is one of the motivations behind the drive to "go small and go fast" – patents expire and become worthless.

This is why some companies, like First Light Fusion, prefer in most cases to protect their IP with trade secrets rather than patents. Filing a patent means that (a) your invention is now in the public domain and (b) the clock has started ticking on the date at which it will expire (and the value of the patent declines with each passing year). Trade secrets do not have these downsides. Start-ups also often prefer trade secrets because managing a large patent portfolio can be expensive and requires dedicated professionals with expertise in patent management.

The popularity of trade secrets in the fusion industry means that the publically available data on patents is likely to be a gross underestimate of overall private sector IP.

Intellectual property is a more important consideration for private companies and investors than it is for national governments. For example, UKAEA does not pursue a strategy of aggressively protecting intellectual property.

To maintain a competitive advantage in a field like nuclear fusion it is more important to build up an industrial base of skills, technological know-how, and supply chains, which is what the next chapter explores.

Impact of UKAEA R&D

Overview:

- UK Government commissioned a study into the impact of the UK's public investments in UKAEA fusion research up to now.[159]
- It looked backwards only and did not consider the future benefit of fusion research.
- The total economic impact of UKAEA to the UK economy is estimated to be between £1.3 billion and £1.4 billion in Gross Value Added (GVA), for the period 2009/10 to 2018/19.
- In terms of employment, it is estimated that UKAEA activities and ITER-related investments support between 34,880 and just over 36,900 job years.
- The return on the UK Government's investments in UKAEA is estimated to be between £3.7 million and £4.1 million of Gross Value Added to the UK economy and between 100 and 106 job years supported for every £1 million invested.
- These figures do not capture impacts from non-UKAEA and ITER UK contracts.
- The figures also do not capture the contribution UKAEA has made to fusion research and adjacent technologies.

Scientific impact:

- Survey respondents overwhelmingly believed that UKAEA had a strong or very strong international standing.
- UKAEA ranked as the third top institution in the world on the number of fusion research outputs.

Other, non-monetised impacts:

- Improvements in skills leading to a higher skilled workforce;
- Knowledge transfer between UKAEA and UK Industry as well as academia;
- Improved fusion reactor designs, and help in the consideration of regulatory standards for fusion;
- Contributions to UK public policy and strategy;
- Contributions to public awareness of fusion, and attracting new talent to the fusion sector via UKAEA's outreach and public engagement activities.

Indirect spin-out companies:

- Tokamak Energy
- Oxford Technologies
- Reaction Engines

Chapter 9
UK fusion activities and capabilities

This Chapter includes:

- Details of the main UK-based fusion research projects
- What components and services the UK is directly contributing to the ITER
- An analysis of the fusion supply chain
- The opportunities for scaling up domestic capability

Introduction

As outlined in the 2020 London Economics report[160], the UK is a global leader in fusion R&D. Many decades of designing, constructing, and operating fusion experiments has built up significant expertise and more than 30 years of operating JET has enabled UKAE to build up expertise in key areas such as tritium handling and remote maintenance.. However, each of these experiments are bespoke devices whose primary purpose has been to develop scientific knowledge and/or to test physics or engineering principles.

The development of supply chains for emerging technologies can be divided into four stages.[161] It begins with basic research (Stage 1), when manufacturing processes are unproven and there are no commercial suppliers. In Stage 1, key components are bespoke and produced by laboratories themselves and specialist companies. In the final stage of development, stable new technology, products have been standardised and there is a mature commercial supply base for components. These stages of supply chain development will broadly be in parallel to the higher level "Four phase approach of fusion development and deployment" outlined in Chapter 3.

Moving through these phases requires a significant amount of time and investment. Before exploring how the UK might achieve this, it is worth outlining the current activities and capabilities.

"

Through design and construction of an engineering demonstrator, the UK could gain the state of the art knowledge… and UK suppliers could then develop this into an industrial capability with a view to later commercialisation.

UKAEA domestic facilities and capabilities

The UK Government announced funding for new Fusion Technology (FT) and Tritium Advanced Technology (H3AT) facilities 2018 with an initial £86 million investment from the Industrial Strategy Challenge Fund.

The main ongoing research activities at UKAEA include:

- Host and lead participant in the Joint European Torus (JET) programme, the main precursor to ITER in the global push to develop fusion energy;
- Experiments on the MAST Upgrade (MASTu) spherical tokamak;
- A theory and modelling programme which studies key areas of plasma physics and predicts performance of future tokamaks such as ITER; and studies of the materials and technology needed in ITER and fusion power stations.

The new FT and H3AT facilities – based at Culham Science Centre and a new UKAEA facility in Yorkshire, will be ready in 2022. Key capabilities will include CHIMERA – is a high flux and heat testing device to test fusion components in realistic fusion conditions and equipment in H3AT (described as a "World-first tritium research centre") which, will study how to process, store and recycle tritium.[162,163]

These will supplement an already strong UKAEA technology programme, comprising:

- **The Materials Research Facility (MRF)** is part of the National Nuclear Users Facility (NNUF) initiative[164] and provides equipment for the micro-characterisation of materials.
- **Remote Applications in Challenging Environments (RACE)** is a partner in the ITER Neutral Beam RHS project led by Jacobs Clean Energy. RACE is also a partner in the development of the Divertor Remote Handling System design led by Assystem.[165]

The goal is to support UK industry to win £1 billion of fusion contracts, in addition to over £500m of ITER contracts already secured by UK businesses.[166]

UK contributions to ITER

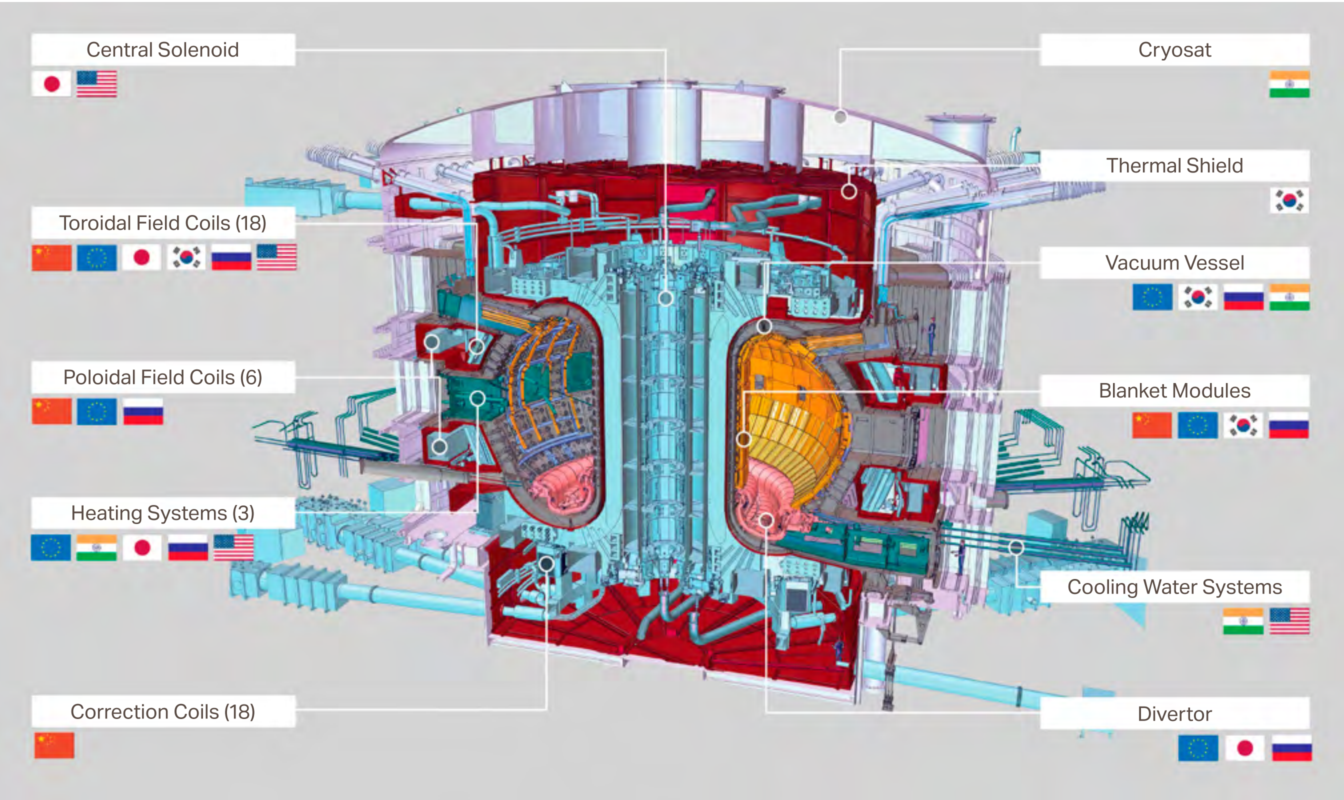
Much of the current research of UKAEA is designed to allow the UK to contribute to the success of ITER with EU partners through structures for fusion that have been important since JET was established in the 1970s.

The scale of ITER and the fact that so many of the components, materials, and systems required to make the project a success define the limits of current technology across a whole range of topics: magnets and superconducting materials, plasma control, vessel and heat removal and exhaust design, blanket technology, etc. This means that it is by necessity a global endeavour. **Figure 12** below shows the main components of the ITER tokamak and the members who are contributing to their design and manufacture.

The UK's particular contribution to ITER is quite broad, much of it coming via or with the support of UKAEA, and ranges from:[168]

- Development of remote handling systems;
- A member of the architect engineer consortium for the tokamak building;
- Specialist welding development;
- Design consultancy – including electro-magnetic, optical, thermo-dynamic, radiation modelling of systems for providing plasma heating, tritium breeding and measurement;
- Supply of technical specialists into many ITER design teams;
- Metrology system design and support services;
- Divertor design work;
- Tritium handling.

Figure 12: Tokamak components and the ITER members involved[167]



At least 40 UK companies are involved in ITER providing over 500 million Euros of contracted equipment.[169]

Many of the key components for ITER are one-off and bespoke and manufactured by national laboratories with expertise provided by specialist engineering companies. Even at a global level, the knowledge, skills and capacity to build a fusion power plant are scarce. This will be even more pronounced at the level of individual nation states.

In the UK, the supply chain for components and materials necessary for the development of commercial fusion reactors is mainly at immature levels of development. Tokamak Energy, for example, import all the ReBCO used in their high temperature superconducting magnets from suppliers located in US, Japan, Germany, Russia and China.[170] Also, few of the major components for ITER are being manufactured in the UK. If the UK is going to lead on the construction of a commercial fusion power plant in the future, it will need a major effort to build capacity and expertise.

Scaling up domestic UK capacity

Mature supply chains for fusion do not currently exist, except in the narrow sense that some companies/countries are producing components for experimental devices such as ITER. Know-how developed on large experimental systems like ITER will be useful for later commercialisation, but these systems are pre-commercial and their suppliers were mostly not selected by competition. Therefore it is not certain that the same suppliers will succeed in the future.

Leading on the design and construction of a commercial scale demonstration plant will involve many challenges. It will require developing and validating technology that is still at the R&D stage and then scaling up production to orders of magnitude of current levels.

Federici shines some light on the key technological challenges for the fusion R&D programme.[171] The major high level technical challenges in ITER have been summarised in a paper written by the ITER Joint Central Team and Home Team as follows[172]:

- Unprecedented size of the super conducting magnet and structures;
- High neutron flux and high heat flux at the first wall/ shield blanket;
- Extremely high heat flux in the divertor;
- Remote handling for maintenance/intervention of an activated tokamak structure;
- The first fusion machine with large radioactive inventory;
- Unique equipment for fusion reactors such as fuelling, pumping, heating/current drive system, diagnostics, etc.

In addition to this, novel plasma physics and plasma diagnostics are at the limit of current technology.[173] A more detailed analysis of some of the technical challenges is given in the Appendix to this report.

At a more granular level, the manufacture of ITER components and the running of the experiment will require techniques, processes, and materials that are relatively immature or completely novel. Surrey[174] has outlined some of the main engineering challenges in fusion demonstrators and assigned them technology readiness levels. Her results are reproduced in **Table 6**.

However, this immaturity also provides an opportunity. If the fusion industry can reduce costs over time in the ways explained in previous chapters so that it can compete on electricity/energy price with comparable technologies, then the size of potential market could be very large.

Table 6: ITER key manufacturing techniques and materials

ITER Key Manufacturing Technique	TRL
Water PHTS	10
Tig & Arc welding	10
NDT	9
Explosion bonding HIP	8
Laser welding (steel)	8
He PHTS	6
Tritium plant	4
Laser welding (unconventional)	3
Tritium permeation barrier coating	2
Fusion NDT	0

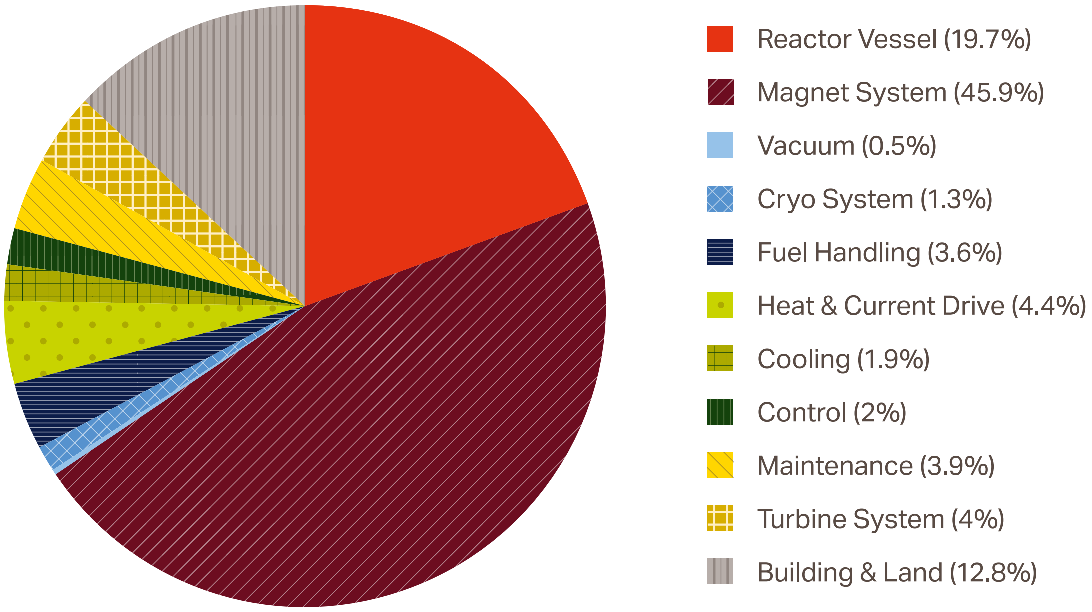
ITER Key Material	TRL
Tungsten	9
High tensile steel	7
RAFM steel	7
Powder additive Manufacturing	7
ODS CU	6
Vanadium alloys	4
Lithium breeder ceramics	4
Beryllium multiplier ceramics	4
Tritium permeation barriers	2
Lithium production	1

Figure 13 (which is **Figure 4** replicated) gives an indication of the system and component costs of a FOAK fusion power plant. Sorbom[175] in the study of ARC provides cost estimates based on a mark-up factor applied to material costs. They use this approach because they have a detailed concept design and can therefore calculate material volumes. Initial estimates for ARC show that magnets and blankets are the largest components (1,440 & 5,760 tonnes respectively) and have the highest material costs. Magnet system material costs could be between 50% and 60% of the total cost of the fusion device. Superconducting materials may be the between a third and half of the total material cost – even though the ARC project has used what were at the time low (future) costs[176] for the more than 5,000 km of REBCO tape required for ARC.

Magnet systems – toroidal, poloidal and shaping coils – are crucially important as all new designs use higher field strengths to obtain better performance and high temperature superconductors are a way of achieving these aims. Their design is discussed at length in both fusion technology[178,179,180] and system[181,182] studies. Magnet systems are at the heart of fusion technology and also are the key to its economics and therefore for supply chain development. If the UK is to build an engineering demonstrator and in the longer term produce fusion power plants, it will need to develop magnet design and manufacturing capability.

Superconducting material producers, whether low temperature Niobium-Tin or the currently much more expensive but higher performance, high temperature REBCO type, will be important, but fusion magnet system designs are specialised and are at an early stage of development. There is an opportunity to catch-up if R&D funds are made available for demonstration and learning.

Figure 13: Distribution of direct capital "overnight" costs for 500 MWe Early technology DEMO1[177]



There are certain other specific development needs, other than magnets, that could present opportunities for UK companies to develop important expertise and they include:

- Diverter design: The UK has been leading on the ITER divertor design and with Super-X part of the MAST Upgrade it has developed and shown a way of designing this crucial part of the tokamak partly through a system design that distributes the heat load over a much extended surface area, and the design of the materials and cooling system to remove unprecedented heat fluxes.
- Vessel materials: JET & ITER are looking at vessel materials that can last longer in the very high neutron fluxes that will exist within a commercial scale fusion device. UK has a strong capability in these materials in part because they have similarities to fast reactor materials – high temperature and high neutron flux and energy.
- Blankets designed for breeding tritium. This research is especially important for creating fuel necessary for securing a continuous fusion reactor.
- Manufacturing & joining technology: As outlined by Surrey, advanced joining techniques will be crucial to any commercial fusion programme and it is an area in which the UK already has significant expertise (page 56 – Impact of UKAEA R&D).

Through design and construction of an engineering demonstrator, the UK could gain the state of the art knowledge on these crucial technologies within UKAEA and UK suppliers could then develop this into an industrial capability with a view to later commercialisation.

If the UK is to commit to leading a commercial fusion demonstration programme, the main options for supply chain development strategy would be:

1. Use current best-in-class suppliers (ie largely foreign as for EPR) of key components and systems, from around the world in the design – for operation in 2040 – with an aim of having a 'UK' design and global supply chain for local use and for export.
2. Fund a crash programme of key technology demonstrations using UK companies and incorporate these into the design and project.
3. Select a strategic partner/country and share the costs and benefits of option 2 with that country.
4. Mix and match on the above options.

Committing to an engineering demonstrator, such as STEP, in addition to a later >1 GWe power plant, would require a substantial commitment of funding, but it would have the benefit of creating an opportunity for UK companies to develop the skills and supply chains to put fusion on a path to commercialisation. First mover countries will also have to develop the regulatory environment. This means having a key influence over any future global market. Having a regulatory regime that becomes the international standard could streamline the path to exporting technology internationally.

Should this path be taken, the design choices made for STEP will be important and require careful consideration as they will strongly influence the forward programme of enabling R&D and ultimately the commercial fusion plant.

UK manufacturing case studies

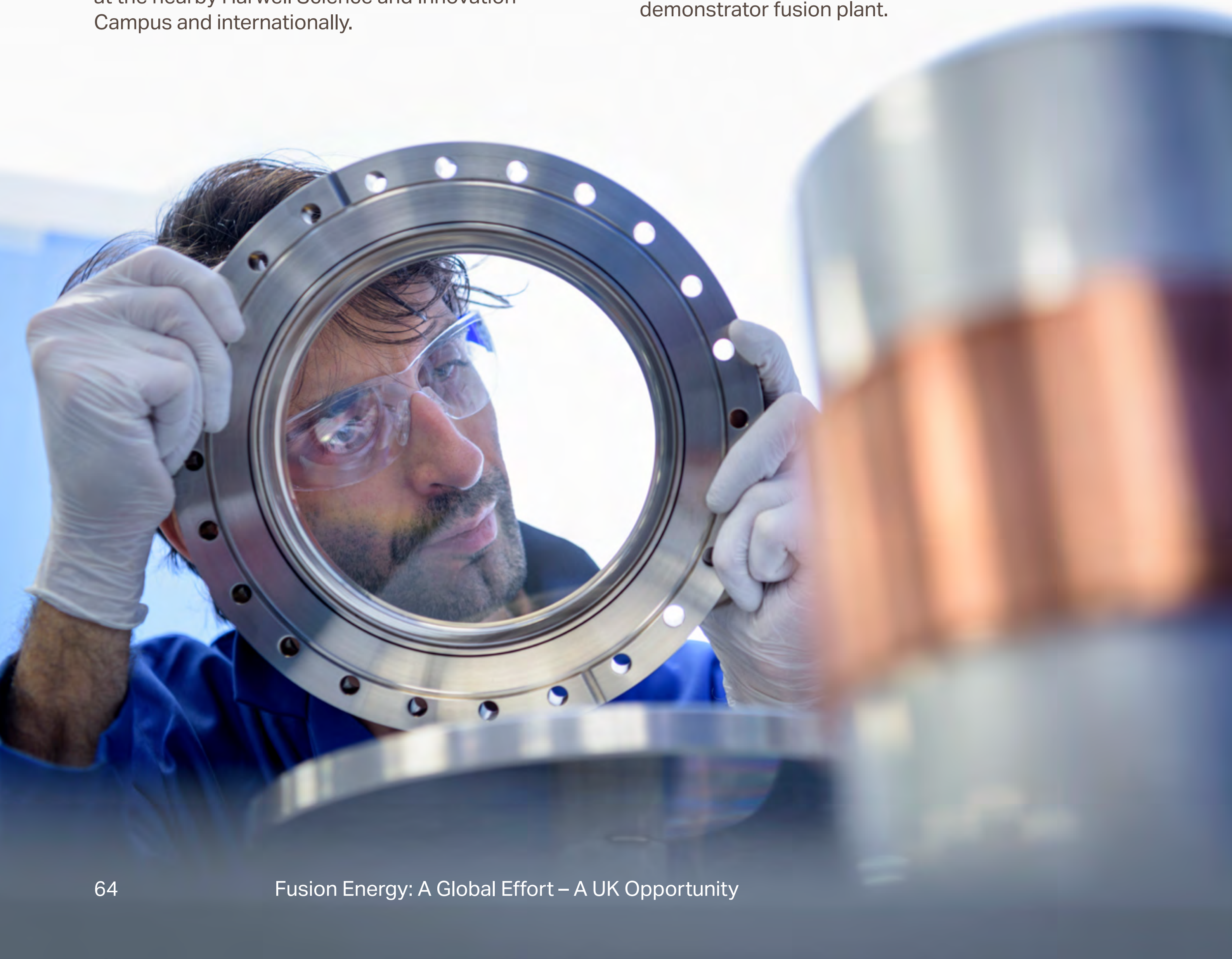
UK specialists in joining techniques

Over many decades, the UK has built up expertise in advanced joining techniques. Some of this is due to a strong and broad R&D base, meaning a high demand for bespoke engineering solutions, while some of it is specifically related to fusion.

The Culham Special Techniques Group[183] **(STG)** has developed expertise in advanced joining techniques over the course of its 40 years history. As well as being the onsite problem solvers for engineers in the UKAEA, the small team of specialists sell their services in other industries that require services that often cannot be provided by the private sector. This includes contributing to particle physics experiments at the nearby Harwell Science and Innovation Campus and internationally.

Similarly to the STG, **TWI**[184], or **The Welding Institute** as it was once known, has a long history, having been formed in 1946. TWI is a go-to organisation for advanced joining techniques, including laser welding, and is credited with having invented friction stir welding in 1991. Now an international research and technology company, it sells its expertise to sectors as diverse as aerospace, oil and gas, and medical equipment.

The Nuclear Advanced Manufacturing Research Centre (NAMRC)[185] is enabling companies to capture key technology for new developments. For example, much of the Rolls-Royce small modular reactor manufacturing technology development is being conducted at NAMRC. This complementary expertise could be the vehicle for fusion industrial R&D and bridge the gap to an engineering demonstrator fusion plant.



Chapter 10
The opportunity to lead

This Chapter includes:

- Potential obstacles to commercial fusion energy
- The opportunity for the UK

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Countries that develop the regulatory environment will have a key influence over any future global market. Having a regulatory regime that becomes the international standard could streamline the path to exporting technology internationally.

Potential obstacles

Averting an overly burdensome regulatory regime.

The regulatory environment for commercial fusion reactors in the UK and abroad must also be established. A clear and proportionate regulatory environment, as recommended by the Regulatory Horizons Council[186], will facilitate the development of licensable technologies and reduce deployment timelines, cost and investor risk. Culham is not a nuclear licenced site, and the Environment Agency, as the primary regulatory authority, has granted permits to UKAEA for accumulating, holding, and disposing of radioactive material.[187]

The regulatory environment for commercial fusion is currently being determined in the UK[188] and the US[189], while ITER is subject to oversight by the French nuclear fission regulator.[190] In a 2021 green paper, the UK Government indicated that it will not seek to impose the burden of being a secure nuclear site on future fusion power plants.[191] To an extent, variations in regulatory environment between countries could inhibit export of fusion reactor technologies through additional licensing requirements, country-specific design modifications to the design and supply chain.

Communicating the hazards

The volumes of radioactive waste produced by fusion reactors are orders of magnitude lower than for fission. It is impossible for the fusion reaction to grow unchecked, as a disturbance in the plasma will lead to it cooling and the reaction naturally being terminated. The main radiological hazard associated with a fusion reactor is therefore the potential for tritium release into the environment. Nevertheless, both the potential for a release and the maximum amount of radiological material that could be released into the environment are extremely low.[192] It is notable that small amounts of tritium are used in radio- pharmaceuticals and are disposed of as part of hospital waste.[193] Therefore, the high safety and low radiological hazard of a fusion reactor should be factored into a rigorous, clearly defined, and proportionate regulatory environment.

In communicating the benefits of fusion, this inherent safety and low radiation risk should be emphasised. A large potential market exists especially in countries/regions where fission is not accepted for reasons of public acceptance or international politics. Also, in order to build individual greenfield sites, the local population will need to be convinced that this does not present a hazard to human health.

The development "valley of death"

Government support in the initial stages of development and deployment will be required to progress fusion to a stage where it can compete on its own merits in a commercial environment. A key enabler of the successful delivery of fusion energy is a stable policy and financing environment coupled with a focus on achieving results on the shortest possible timeline. Many long-term state-funded efforts to commercialise advanced fission reactors have ultimately stalled, for example the fast breeder programme in the UK[194], the ASTRID programme in France [195], and the Next Generation Nuclear Plant programme in the US[196] A multi-decade R&D programme requires continuity across multiple political cycles, with a commitment to meet rising costs as the programme enters delivery mode, as it is more expensive to build something than to design it. If there are delays at various stages in financial authorization and decision making (eg, final investment decision for the engineering demonstrator, final investment decision for the performance demonstrator), then these can be expected to impact the overall programme. Planning and decision making needs to be viewed in terms of required expenditure as well as required time.

Recent years have seen significant increases in private sector investment in fusion power, particularly in the US[197], which is one driver of the more aggressive timelines for commercialization being put forward recently. Nevertheless, return on investment can be anticipated to take decades, and hence a long term view is required to see through the programme to completion for both public and private investors. This must be balanced with active and intelligent programme management that works with the technology developers to meet the timelines stated as part of the case for investment.

Lack of a skills pipeline

Increased investment in skills and a messaging campaign to emphasise that fusion is a long-term career option in an expanding industry will be important. The UKAEA already has active programmes for apprentices, graduates, and PhD students, but if the industry is to grow, the talent pipeline will have to expand commensurately. Training programmes should be expanded in collaboration between Government, industry, and academia, with messaging that emphasises that this is a stable and promising sector to encourage new entrants. Young people will likely be attracted by the high tech environment and the opportunity to work in clean energy, but it is important they are not deterred by a lack of confidence in an immature industry.

The opportunity

In their 2021 fusion strategy document, the UK government set out how it will aim to leverage scientific, commercial and international leadership to enable delivery of fusion energy.[198] It is beginning from a good position. The UK has a well-regarded and expanding public sector fusion R&D ecosystem. Private sector investment is also increasing in the drive to commercialisation. However, as is the case in every country, the fusion manufacturing sector is immature and needs development. Collaboration will be required between public and private sectors to establish the basis for cost effective fusion systems production in UK and for export.

In developing a commercial fusion sector, the UK could be an industry leader, add substantial value while working with international partners, and establish areas of excellence to potentially enter the supply chain in other countries. Compared to nuclear fission, a higher proportion of the costs of a fusion power plant comes in the form of manufactured components, primarily the superconducting magnet systems (in the case of a tokamak) and the reactor vessel. Due to a lack of proliferation concerns, there will also not be the same barriers to the flow of components in and out of nations. These two factors mean that fusion could offer greater export potential than fission. The path to a global commercial fusion market could also be smoothed by developing a common regulatory regime(s) between nations or regions.

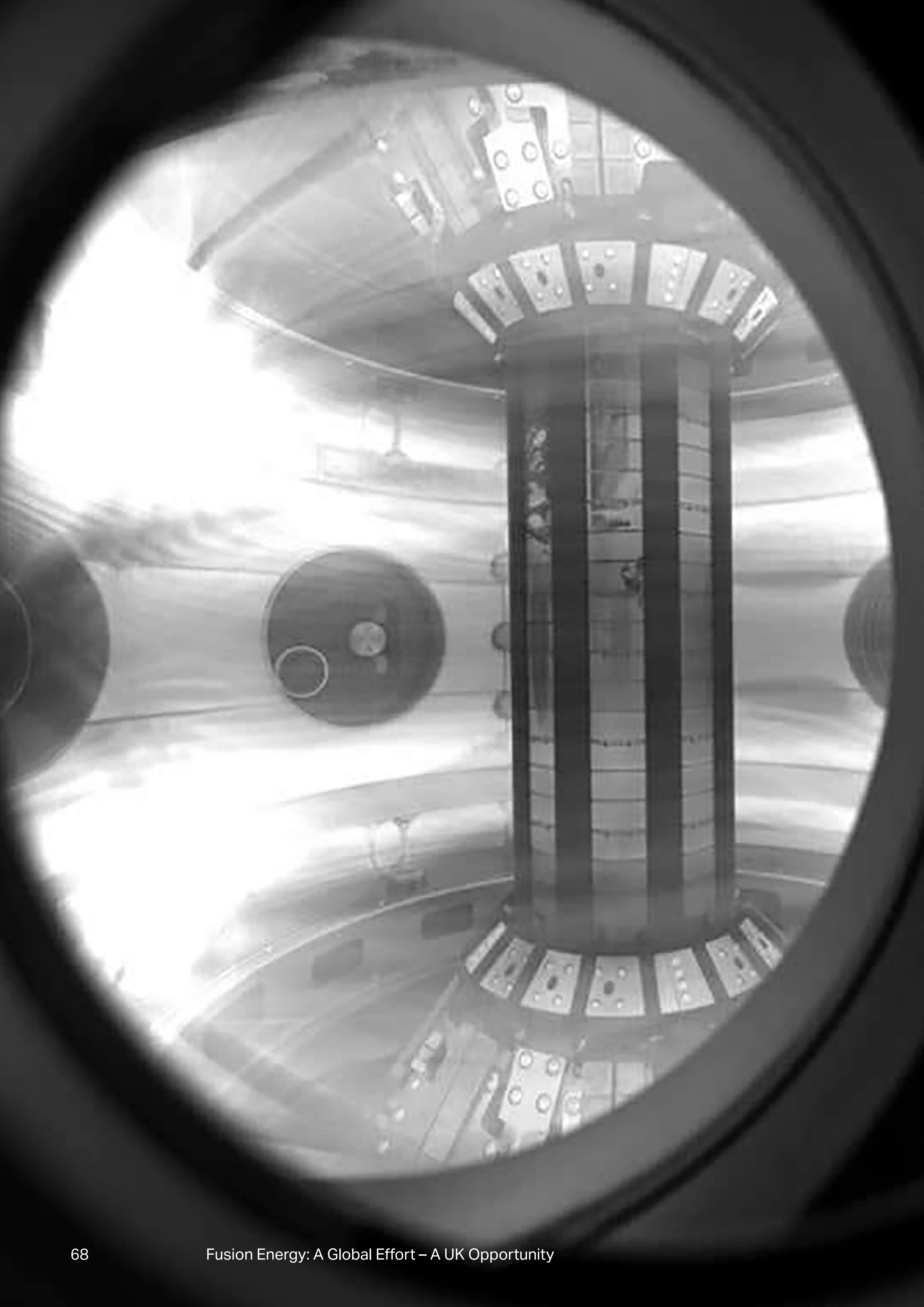
Countries that develop the regulatory environment will have a key influence over any future global market. Having a regulatory regime that becomes the international standard could streamline the path to exporting technology internationally. The UK should therefore lead in advocating for a standardised (and proportionate) regulatory environment in fusion and prioritise work towards this goal.

In addition to this, fusion technology is complex, and the skills required to build and maintain a fusion reactor so specialised, that being a first-mover could deter potential competitors from entering the market. In the event that the fusion industry can hit targets for cost reduction to make commercial plants competitive, this means a global market for the technology and services could be provided by a small number of countries and nations.

In the short-to-medium term, there are positive economic spill-overs from fusion research to other high technology sectors.[199] In the longer term, with significant R&D funding and the right industrial policy, the UK could become a global leader in fusion energy.

Nuclear fission provides a parallel here, but an even starker example is the civil aviation industry, in which over many years has consolidated so that just two companies: Boeing and Airbus have captured a large majority of the market.

Therefore there is a strong motivation for individual nations to be first-movers in fusion energy, but developing an independent fusion industry in the short term would be a major undertaking that would stretch the technical capability and skills resource of an individual nation. Near-term progress in fusion depends on the success of ITER and the associated international R&D effort.



Appendix
Fusion technology development needs

Whilst ITER is primarily a large fusion physics experiment, it will undertake some important engineering testing including testing tritium breeding modules. But it is not a full engineering demonstration of fusion as it does not produce electricity and does not include full tritium breeding cycle.

The additional features of an engineering fusion power demonstrator will need to include: tritium self-sufficiency; economic power conversion; robust remote handling of radioactive material; demonstration of the control of the plasma and safe fault management; and being licensed by a suitable authority.[200]

In parallel with ITER an international programme of the development of key fusion technologies support the design of the EU's DEMO demonstration power plant and similar devices. These technology projects include:

- Blanket options including helium-cooled pebble bed and water-cooled lithium lead, and their related materials and power plant options;
- Seven plasma exhaust system (divertor) design options;
- Three different designs of superconducting magnet coils, including different superconducting materials;
- Maintenance including replacement of life-limited vessel and blanket components.

There are specific major R&D efforts in: Japan – materials and design concepts; China – breeding blanket, superconducting magnets and remote maintenance; US – lead-lithium blankets, vessel materials irradiation; EU – divertor design, vessel materials irradiation.

Other developments are needed.[201] Advances are required both to extend fusion burn for sufficient time to produce substantial energy, and also in the plasma heating systems and actuators.[202] Plasma facing materials must be developed which can sustain the required temperatures and neutron flux. This is a substantial technical challenge requiring significant research and development.[203]

Here, lower power density devices benefit from reduced cooling requirements and neutron flux in the plasma facing components. Reducing the demands placed upon reactor materials reduces technology development hurdles and may increase plant availability due to reduced maintenance outages, and hence electricity output.[205,206]

The helium 'ash' produced by the fusion reactor must also be removed via complex systems called diverters. The neutron flux also has the potential to degrade performance of the magnets, which must be shielded. The design and performance of high temperature superconducting magnets requires further research.[207]

In addition, many other systems are required in an electricity producing fusion reactor. These are at various stages of technology readiness and generally include the following[208,209] (Refer back to page 20 – The elements of a Tokamak Fusion Reactor, for a diagram of the main tokamak components):

- Magnets (for providing the magnetic confinement)
- Vacuum system (to provide the high vacuum environment for the plasma)
- Cryogenic system (for cooling the magnets)
- Systems for tritium recovery and fuel injection into the plasma
- Heating and current drive system (to power the magnets and heat the plasma)
- Heat transfer systems
- Control and diagnostic systems
- Maintenance equipment (including remote maintenance (robotics)
- Balance of plant (turbine, heat exchangers… for producing electricity)
- Systems to reprocess spent reactor components such as blankets, first wall, divertor

The power cycle efficiency depends on the temperature of the heat from the blanket and the related choice of power conversion technology (eg a steam or a gas turbine). For example, at low temperatures 300 C, the blanket may be cooled by water which can feed directly to a steam turbine. For higher temperatures, a gas power cycle may be a more efficient choice. In some higher temperature cases 500–600 C, the blanket may also be gas cooled – using either helium or carbon dioxide.

Current gas turbine designs are not directly applicable to fusion power plants because of significant differences in operating conditions: closed rather than open cycle, choice of working fluid and what will be the optimum pressures and temperatures – probably higher pressure and lower temperature than current gas turbine practice.

Therefore, the power conversion cycle and the related choices of blanket design are particularly important for fusion reactors. They have relatively large house-keeping loads (both to heat the plasma and to cool and maintain the magnets). Therefore the net efficiency (ie power output less house-keeping loads) of the system can be substantially lower than the efficiency of the power cycle. For nearer term technology options, net efficiency may be as low as 25%. With a higher temperature blanket technology, net efficiency may be ~36–42%. For radically more advanced designs with liquid metal-cooled blankets and gas power cycles, net efficiencies may approach 60%. This compares to efficiencies of ~55–65% for combined cycle gas turbine power plants and ~34–41% for the UK fission reactors. Thermodynamic efficiency of fusion power plants is important not for reasons of fuel usage, as it is both cheap and plentiful, it is importance to the capital cost and how this affects the cost of electricity.[210,211,212]

Broadly speaking, fusion technology has the option of adopting early technologies of higher readiness and lower net electricity production, or advanced technologies of lower readiness and higher net electricity production.[213,214]

- Higher gain fusion power plant produces more electricity and operates at higher net efficiency but places more demands on plasma physics.
- More compact tokamaks have potentially lower total capital cost but place higher demands on the plasma physics and on neutron fluxes experienced by the core materials, exacerbated by less room being available for shielding. The engineering complexity is also increased due to greater need for optimization of space and components.
- A higher temperature blanket improves cycle efficiency. The plant produces more electricity and can operate at higher net efficiency. However, this places more demands on the materials of the blanket. Parasitic power demands of gaseous coolants used for high temperature have the potential to reduce the thermodynamic advantage of these higher temperatures. Also, higher temperature gas power cycles would require some turbine technology development.

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