FUSION ENERGY: A GLOBAL EFFORT– A UK OPPORTUNITY.

Institution of MECHANICAL ENGINEERS

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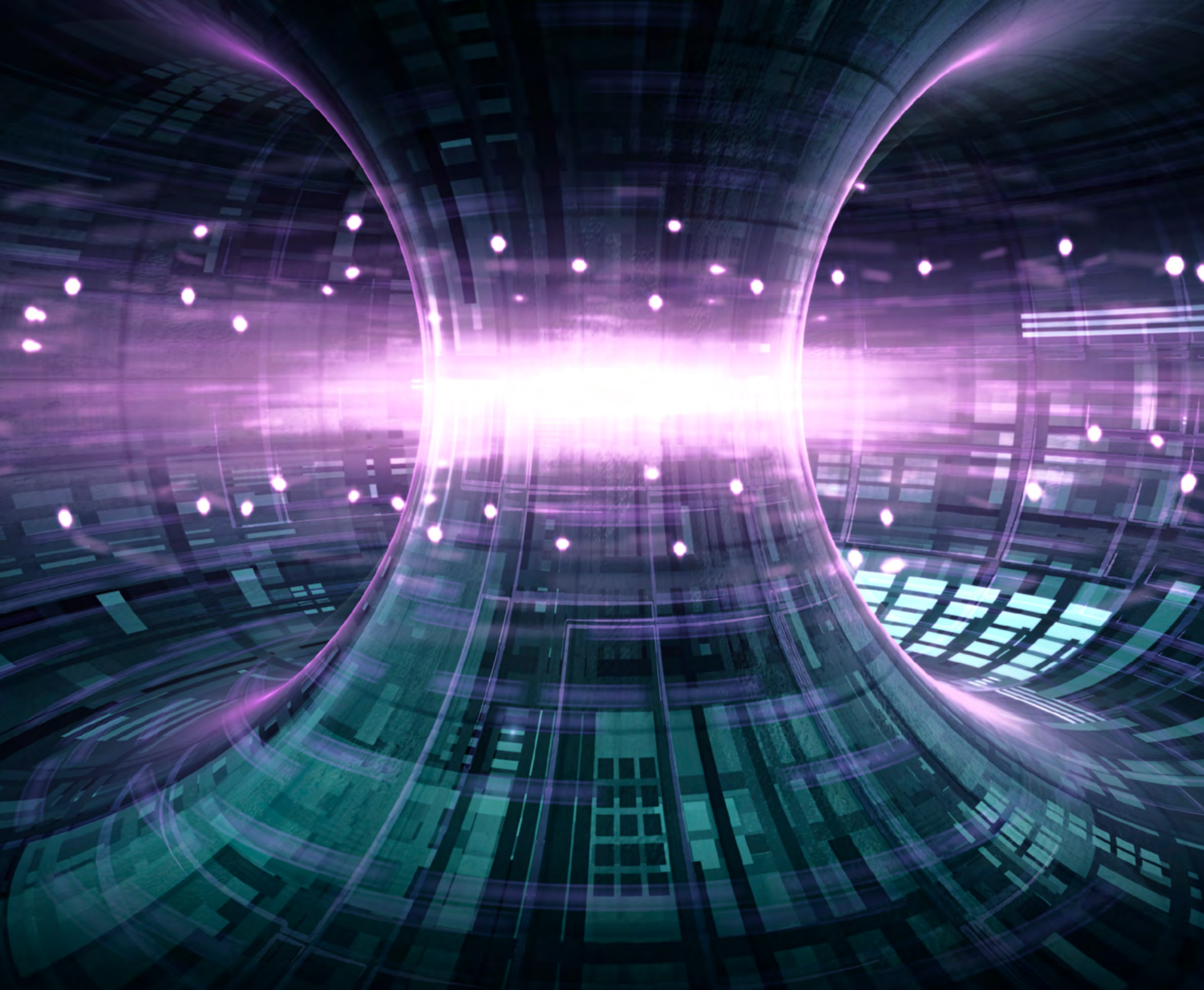
Summary for policymakers



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.

Matt Rooney CEng MIMechE
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.

The full report is available alongside this summary on the IMechE website:
https://imeche.org/policy-and-press/reports

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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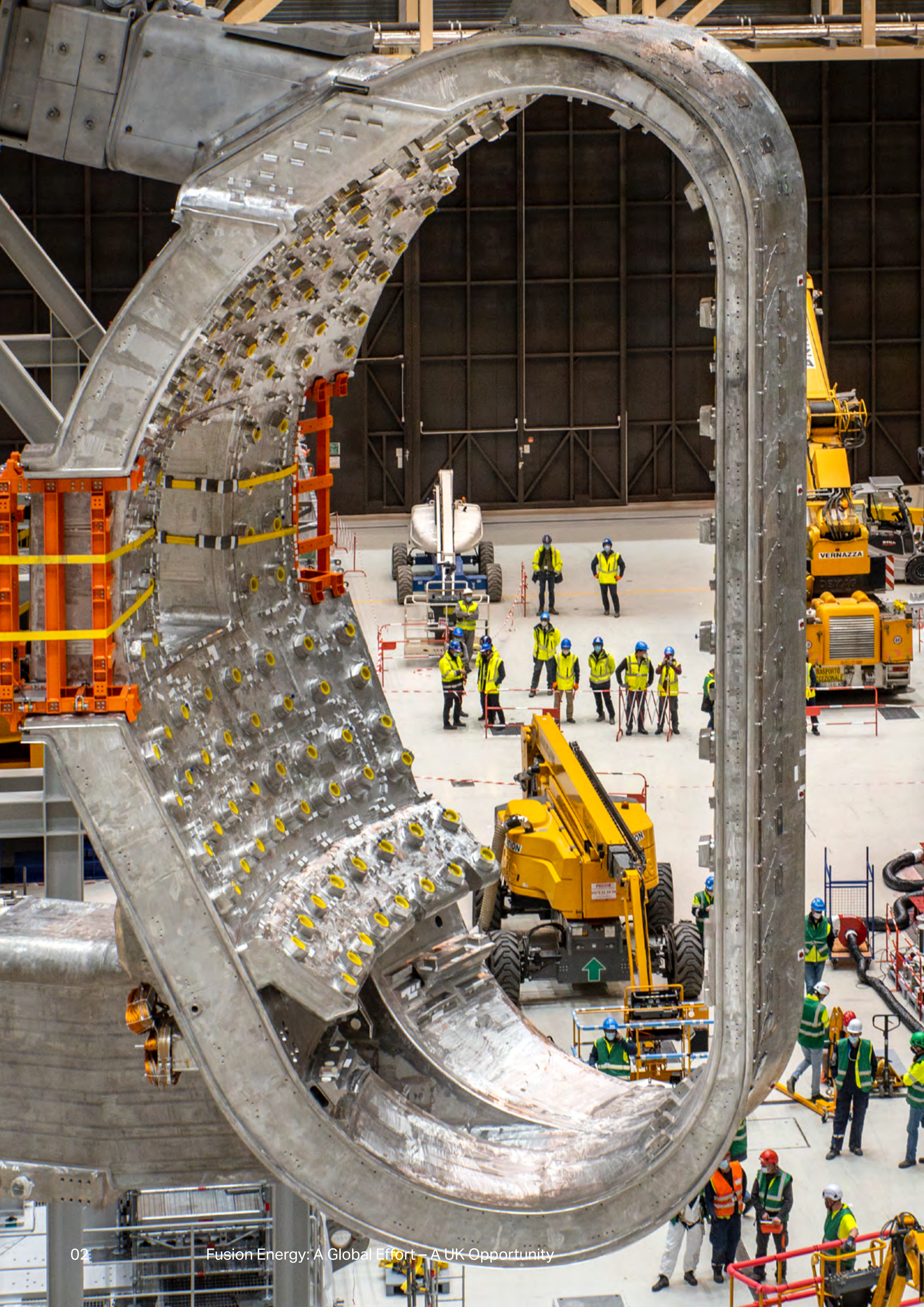
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Introduction

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.

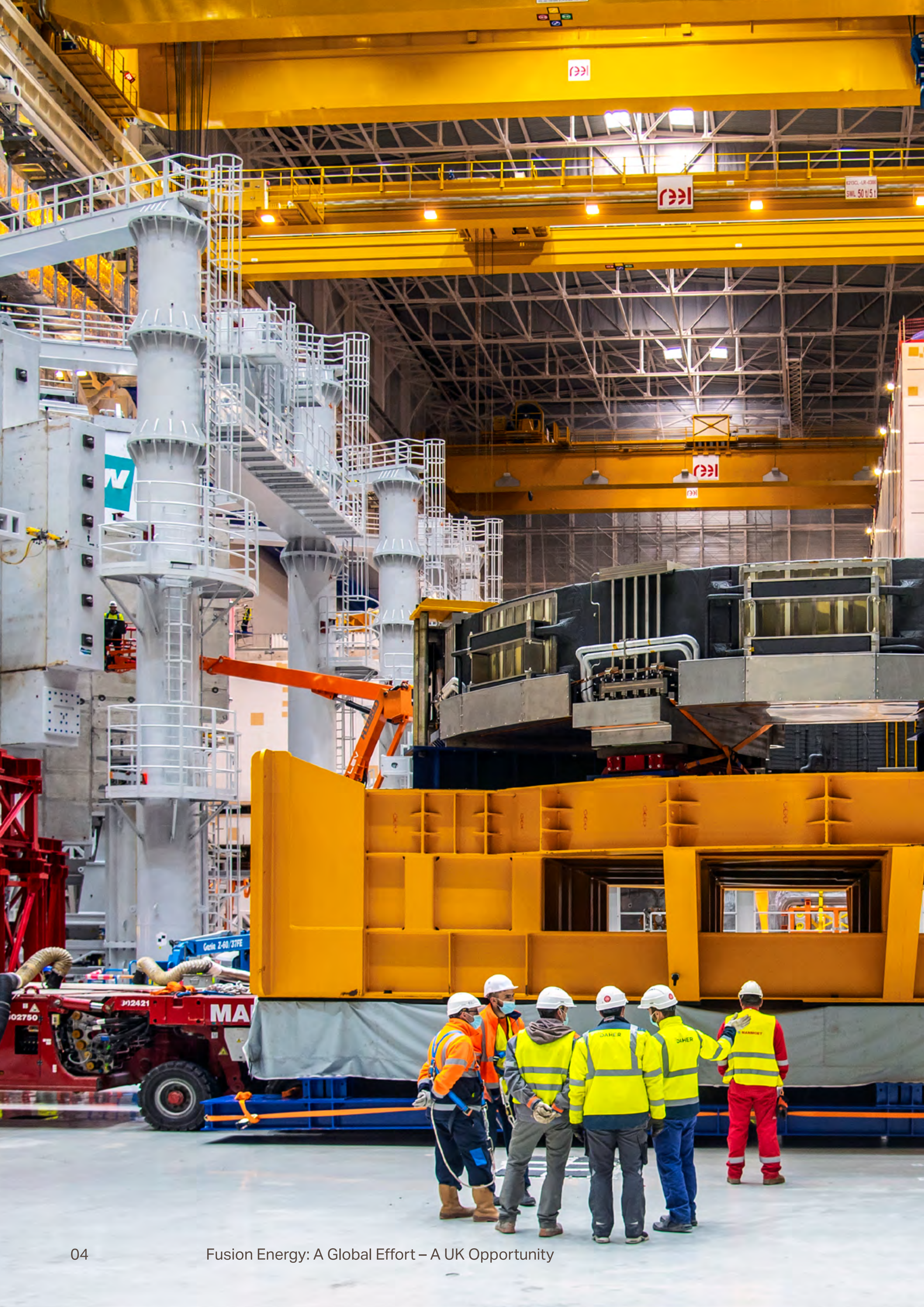
The potential advantages of fusion have been known for a long time. A commercial fusion power plant would be a reliable energy source, with an essentially limitless supply of fuel, and would be low-carbon and produce much lower levels of radioactive waste than a fission plant. Essentially, commercial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

The full report is available alongside this summary on the IMechE website: https://imeche.org/policy-and-press/reports



The role for fusion in a future energy system

The 2040–60 global energy market

Although start-up companies are attempting to accelerate the development of commercial fusion power, it is unlikely to make a substantial contribution to the global energy system until the 2040s at the earliest. The need for fusion must therefore be evaluated according to the energy market 20 or 30 years in the future, rather than that of today. Nevertheless, the demand for low-carbon electricity in the period 2040–2060 is projected to be large and expanding.

The global electricity market for fusion can be estimated using IEA World Energy Outlook forecasts for 2040[1]. An average of 600 gigawatts (GW) per annum of new electricity generation will be required under their Sustainable Development Scenario. While variable renewables will dominate many electricity grids of the future, there will also be a demand for low-carbon dispatchable[2] electricity. As the proportion of intermittent wind and solar power on any electricity grid increases, the total system cost increases at a greater rate. This is due to the variable nature of these sources and the ever steeper requirements for rarely used back-up power as their proportion of total capacity increases. In short, grids featuring large proportions of variable renewables cost more, as they require additional infrastructure, which includes, for example, large-scale energy storage.

In addition to solar and wind power, new generation capacity of 350 GW per year is projected to be required. To meet global decarbonisation targets, most of this will need to be met by low or zero carbon sources, which include nuclear fission, hydro, bioenergy, geothermal, and concentrated solar power. These low-carbon sources represent the potential market. Assuming this level of new capacity continues in the period 2040–2060 fusion will compete in a market of 140 GW per year. If fusion were to take 25% of this market this would be 700 GW over the 20 years to 2060. By way of comparison, the UK's total existing generation capacity in 2020 was 76 GW.[3]

Therefore if fusion can be shown to work and produce electricity at competitive prices in the longer term, the domestic and international market could be very large.

Fusion can complement, or fill the gaps left by fission

A key advantage of fusion power is its potential to access markets that may be unavailable to fission due to political constraints. This includes countries and/or regions with low public opinion of nuclear power or political opposition to construction of new fission plants (eg Germany, Italy, Japan, many US. states). The comparatively negligible volumes of radioactive waste from fusion reactors and very low potential for off-site radiological consequences make public acceptance of fusion power in such regions more likely. In the UK, approval for greenfield construction of fusion reactors should be more straightforward than for fission, for example, and hence may complement the current plans for construction of new fission reactors at existing nuclear licensed sites.

A fusion power plant could produce valuable heat energy in addition to electricity

Fusion reactors may also produce large amounts of low-temperature waste heat, depending on their configuration. This heat could be harnessed through low-temperature cogeneration, for example desalination or district heating. National Grid has estimated that district heating could heat up to four million UK homes in 2050 under low-carbon energy scenarios.[4]

In the longer term, with technological developments, production of high-temperature heat may also be considered as a component of the case for fusion. Possible markets include heat for industrial processes (eg steel manufacturing) and hydrogen production. Such approaches might enable incremental improvement in fusion economics by providing wider system benefits.

UK and global effort on fusion

Public sector R&D

The current international fusion R&D programme is dominated by the tens of billions of Euros being spent to construct ITER. The ITER project is truly international and funded by contributions from the EU (including the UK), the USA, India, China, South Korea, Japan and Russia. It aims to demonstrate fusion feasibility and provide the basis for subsequent demonstration commercial fusion power plants (referred to as DEMO). In addition to ITER, there are many publically-funded R&D projects that are contributing to a global effort in the field.

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 new FT and H3AT facilities – based at Culham Science Centre and a new UKAEA facility in Rotherham, Yorkshire, will be ready in 2022.

Key capabilities will include CHIMERA – 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.[5,6] These will supplement an already strong UKAEA technology programme, comprising:

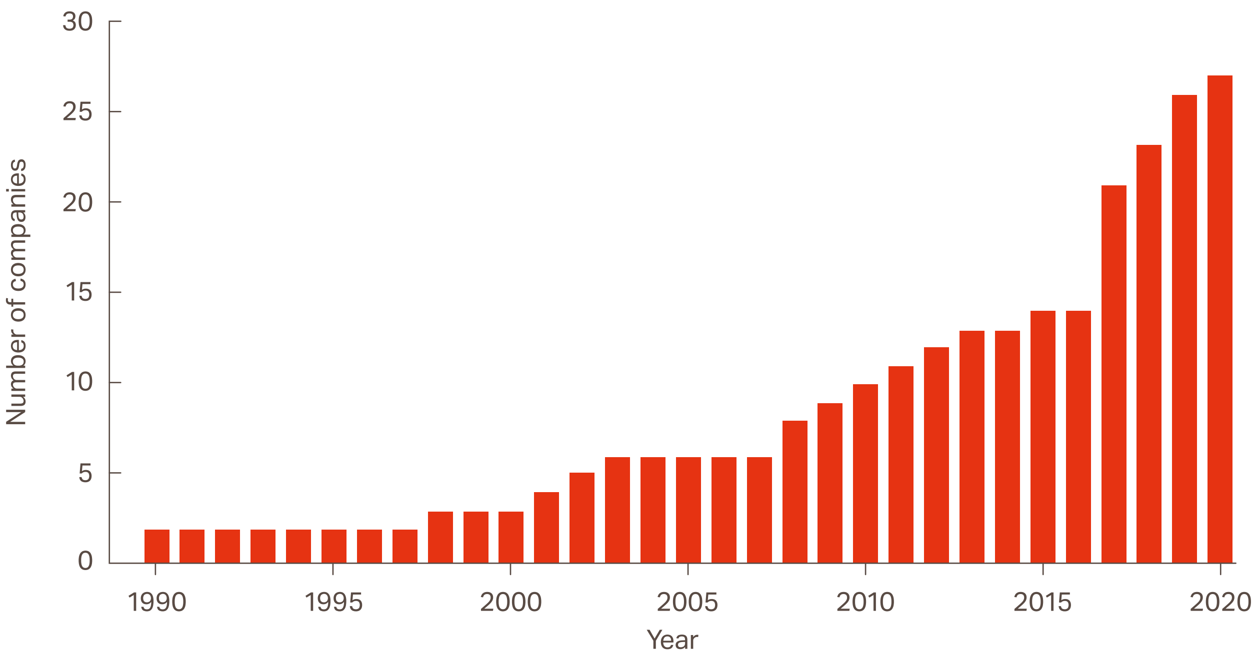
- The **Materials Research Facility (MRF)** is part of the National Nuclear Users Facility (NNUF) initiative[7] and provides equipment for the micro-characterisation of materials.
- **Remote Applications in Challenging Environments (RACE)** is a partner in the ITER Neutral Beam RHS project led by Jacobs Clean Energy. RACE is also a partner in the development of the Divertor Remote Handling System design led by Assystem.[8]

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.[9]

Growing private sector investment

Although the international R&D investment landscape has recently been centred on ITER, private sector activity has been growing rapidly. Globally, more than 15 fusion energy start-ups have been created since 2009. The New York Times has reported that total private investment in fusion is approaching $2 billion.[10] Much of the motivation for this growth lies in the belief that alternative approaches to fusion can be achieved more quickly than the most researched technology, large tokamaks (see page 15 of this report for a diagram of the main components of a large tokamak). This is either through other, less investigated, approaches to fusion (eg magnetised target compression fusion, inertial fusion) or through the design of smaller tokamaks with stronger magnets based on new high temperature superconductors. Two British companies, both based in the "fusion cluster" in Oxfordshire, are those exploring alternative approaches.

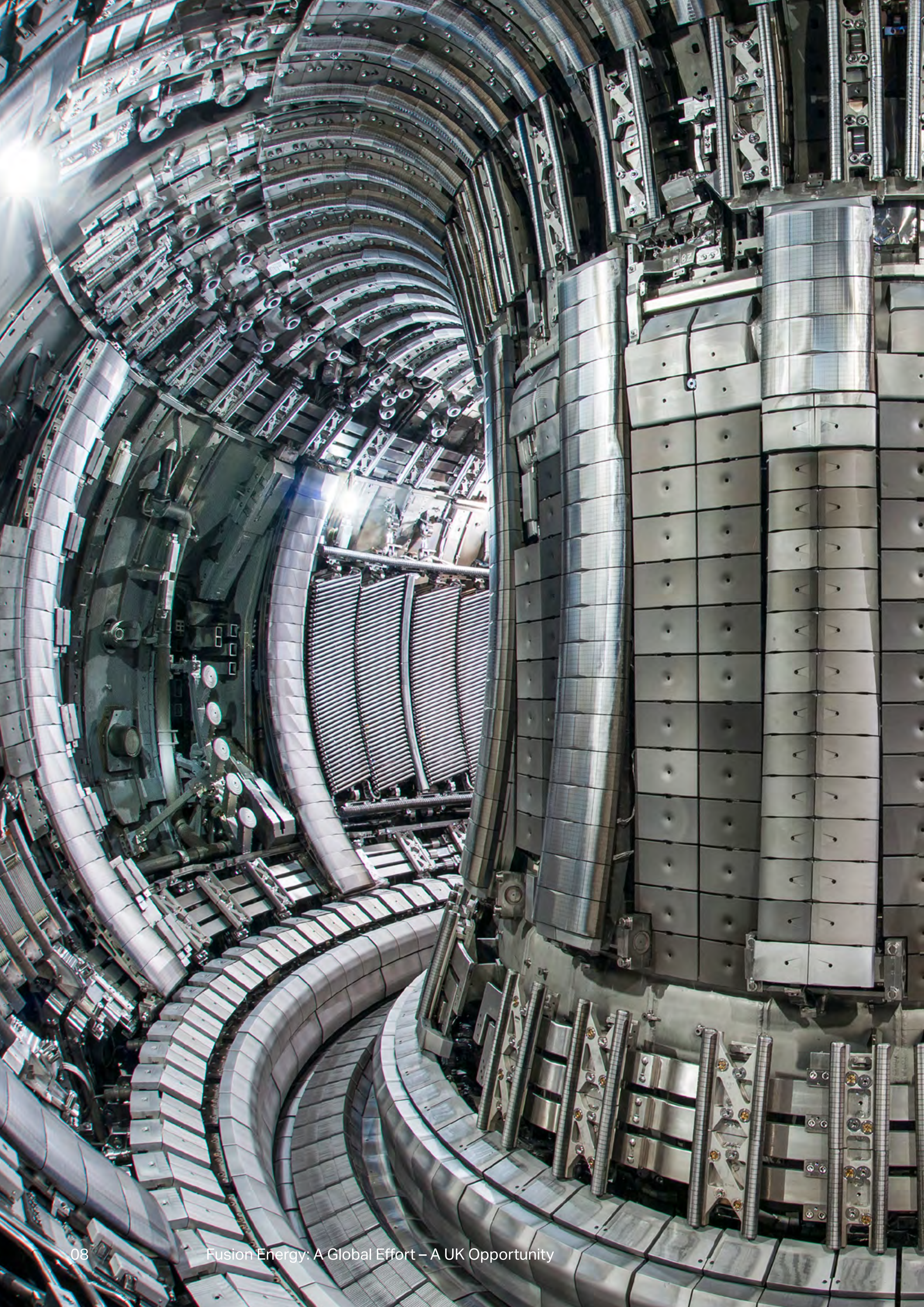
Figure 1: Number of private companies pursuing fusion energy by year of their creation[11]

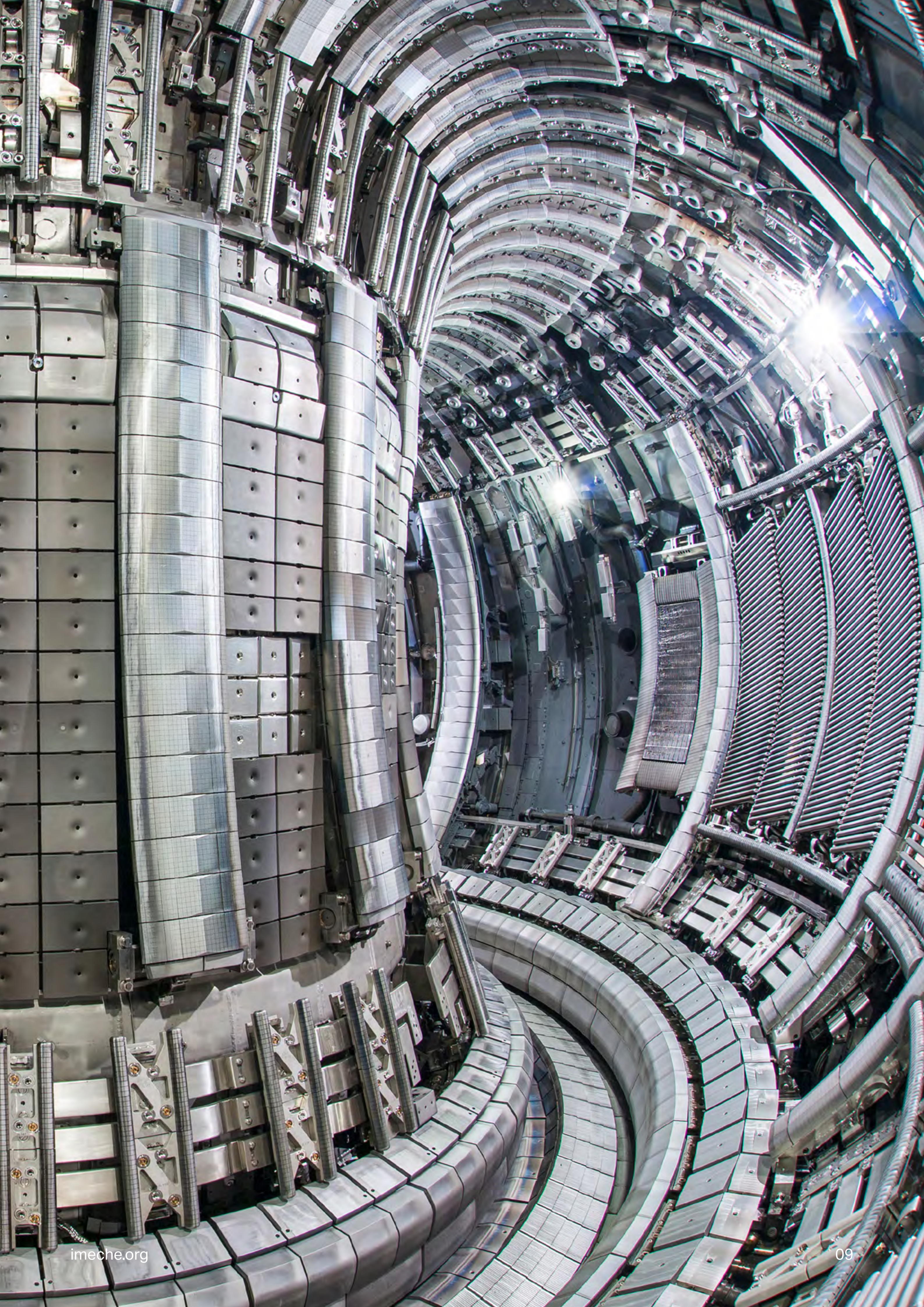


Tokamak Energy, established in 2009, aims to pioneer development of commercial fusion energy based on compact spherical tokamaks with high-temperature superconducting magnets. It holds over 50 patents, most of which relate to their magnet technology, with applications that go beyond fusion energy.

First Light Fusion spun out from the University of Oxford in 2011, and is aiming to use high pressure shock waves obtained in collapsing bubbles in a liquid to achieve fusion conditions. They hold nine patents and 160 trade secrets.

TAE Technologies, based California, is another company with ambitions of an accelerated path to developing commercial fusion. However, TAE is not just a fusion energy company. They use their complementary expertise to develop products and services for other markets, including power management systems – both for electric vehicles and for local electricity grids – and life sciences. 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 allow more precise targeting of tumours, with less damage to healthy cells than traditional radiotherapy.





The road to commercial fusion

There are likely to be four phases to the deployment of commercial fusion power plants, as mapped out below.

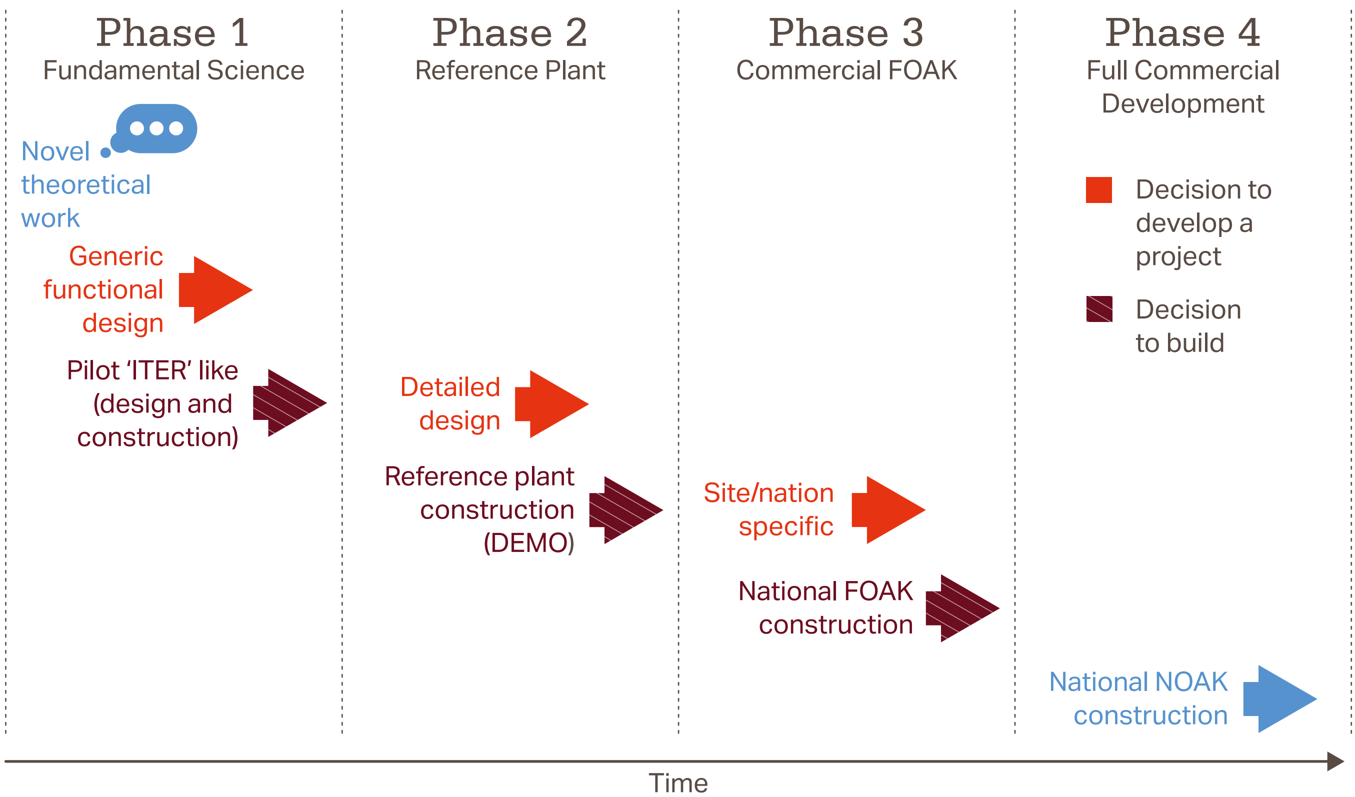
Phases 1 and 2 can be led by governments or the private sector, but both will need public funding. Phase 3 typical requires some form of government subsidy. Phase 4 is attempting to compete in a competitive market without subsidy.

Fusion is currently in Phase 1 and this will likely continue until ITER, or perhaps one of the many start-ups, demonstrates technical viability in the 2030s. The UK has recently announced £220 million of funding for a design study of a demonstration plant, the Spherical Tokamak for Energy Production (STEP), which aims to begin operation by 2040, and would take fusion into Phase 2.

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 to pursue further R&D with the aim of achieving superior performance, which in turn will improve its economic viability. In the development and deployment programme, a key question is then: "At what point do we freeze the concept design stage and begin the detailed design and construction of the demonstrator?"

Technological advances that would improve the competitiveness of fusion include high neutron materials, low-cost high-temperature superconducting magnets, improved breeding blankets, and higher efficiency power conversion cycles. For example, developing materials that can withstand the harsh environment of a fusion reactor for longer periods reduces the need for regular component replacement.

Figure 2: A roadmap to commercial fusion



After completion of Phases 1 and 2, the success of Phases 3 and 4 will depend primarily on the ability of the industry to bring down costs to a level where they can compete with comparable low-carbon technologies.

Costs are currently uncertain due to fusion still being an experimental technology and due to the inherent uncertainty in estimating the cost of complex systems. Forecasting the future costs of fusion is even more difficult because of the long time-scales that are being considered. Nevertheless, for fusion to be competitive beyond 2040 with renewables (including back-up for reliability), generation costs will likely need to be below ~£70/MWh in current prices.

As has been the case for many novel technologies in the past, economic modelling using the limited data that is publicly available suggests that the cost of electricity from a basic large tokamak, based on the ITER design, would be higher than this benchmark, even with the reduction in costs from production learning. As has also been achieved historically in the energy sector (eg offshore wind) and other industries (eg aerospace), cost reductions can be achieved by further developing the technologies and their supply chains.

Shorter build times and lower financing charges improve fusion energy costs and hence competitiveness. Small fusion power plants have the potential to offer a faster route to market, but initially they could have higher cost barriers because of dis-economics of scale. These can be offset both by the economy of multiples[12] and by shorter build times.

Building capacity will also be necessary to bring down costs. To maintain a competitive advantage in a field like fusion, it is important to build up an industrial base of skills, technological know-how, and supply chains. Existing supply chains are immature and not ready to support commercial deployment anywhere in the world. An advantage of a new UK-based fusion demonstration plant would be the opportunity to boost domestic industrial capacity in technologies, including project management understanding, which will be key to the development and future deployment of a commercial fusion power plant.

Potential obstacles to development and commercialisation

In addition to the economic challenge outlined above, the other main potential obstacles to commercialising fusion energy can be categorised as technical, regulatory, political, and the skills pipeline.

Technical

Technical challenges are well known and explored in more detail in the full report. They include confining the plasma, demonstrating much longer stable fusion reactions, breeding and handling tritium[13], validating material properties of key components in extreme environments. What is required to overcome these challenges is stable long term funding, investment in skills, and continued international collaboration.

Regulatory

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[14], will facilitate the development of licensable technologies and reduce deployment timelines, cost and investor risk. The Culham Science Centre 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.

The regulatory environment for commercial fusion is currently being determined in the UK and the US., while ITER is subject to oversight by the French nuclear regulator (that is for the vast majority concerned with the fission technology). 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.[15] To an extent, variations in regulatory environment between countries could inhibit export of fusion reactor technologies through additional licensing requirements, country-specific modifications to the design and supply chain.

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 and maximum amount of radiological material that could be released into the environment is extremely low. It is notable that small amounts of tritium are used in radiopharmaceuticals and hence disposed of as part of hospital waste. Therefore, the high safety and low radiological hazard of a fusion reactor should be factored into a rigorous, clearly defined, and proportionate regulatory environment.

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

Political

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. Examples include the fast breeder programme in the UK[16], the ASTRID programme in France[17], and the Next Generation Nuclear Plant programme in the US.[18]

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 authorisation and decision making (eg, the final investment decision for the engineering demonstrator, final investment decision for the performance demonstrator), 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.

Also, policies need to be established to support the early stages of commercial developments. A relevant example would be the Contracts for Difference scheme that supports the deployment of renewable energy technologies through the payment of a predetermined price for electricity. This price, usually higher than the average price of electricity in the market, minimises the market risk and provides enhanced remuneration for stakeholders that are willing to invest in the development of infrastructure.

Despite the significant increase in private sector investment in fusion power, the return on investment is likely 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 involved to meet the timelines stated as part of the case for investment.

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 have 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 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 to lead

In its 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.[19] 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 both the 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 significant influence over any future global market. Having a regulatory regime that becomes the international standard could streamline the path to exporting fusion 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.[20] In the longer term, with significant R&D funding and the right industrial policy, the UK could become a global leader in fusion energy.

The elements of a Tokamak Fusion Reactor

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 m^3.

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

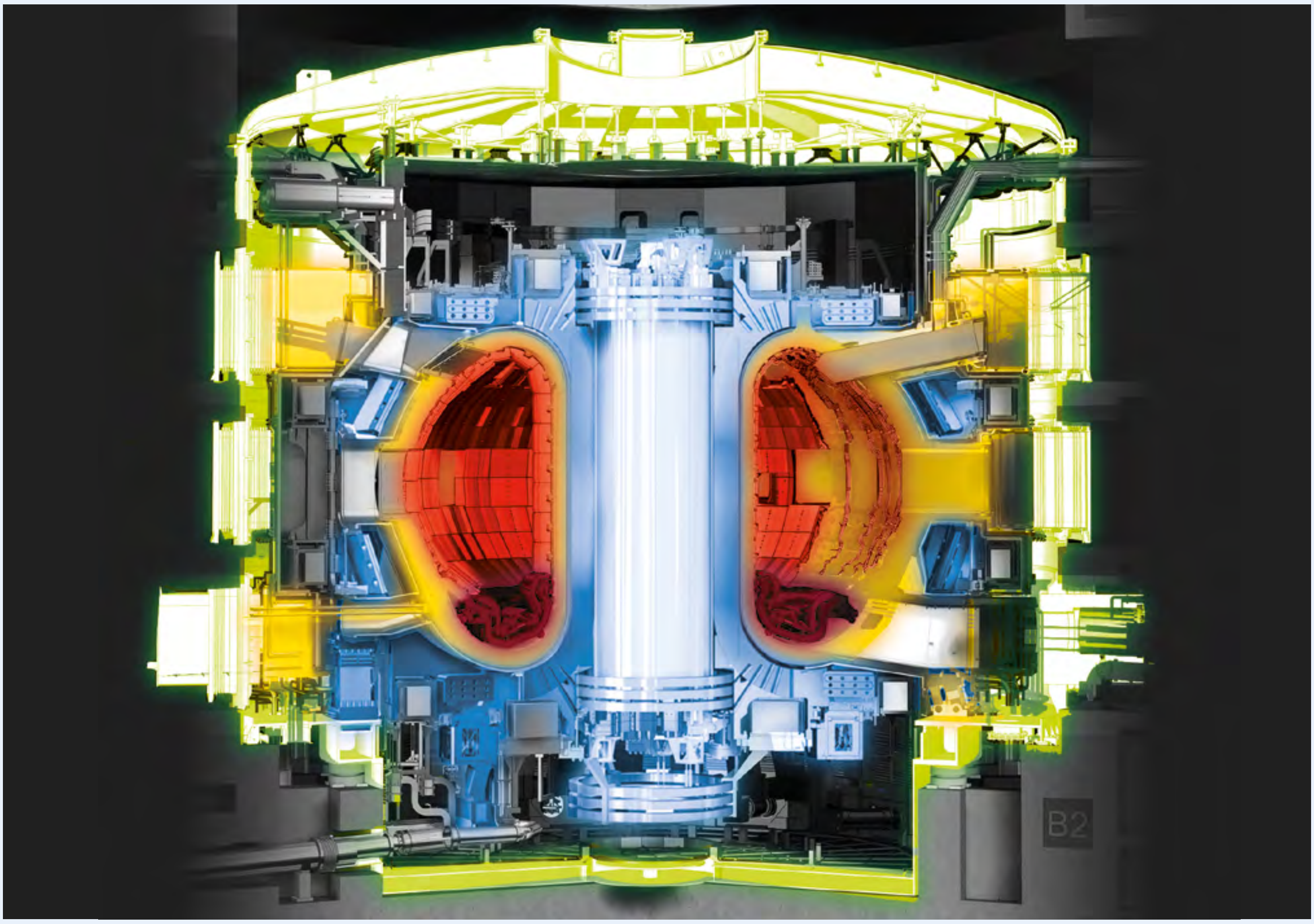
The blanket shields the steel vacuum vessel and external machine components from high-energy neutrons produced during the fusion reaction.

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.



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10 NYT (2021). "Massachusetts Start-Up Hopes to Move a Step Closer to Commercial Fusion". [Online]. https://www.nytimes.com/2021/08/10/technology/commonwealth-fusion-mit-reactor.html

11 Reproduced from: https://www.fusionenergybase.com/article/the-number-of-fusion-energy-startups-is-growing-fast-heres-why

12 Economy of multiples refers to the cost reduction achieved by building and operating nearly-identical systems. For instance the aerospace industry achieved an economy of multiples by building the same model of aircraft thousands of times over and having airline companies bulk-ordering and operating the same model of aircraft. In the power sector the economy of multiples is enhanced when nearly similar plants are built in series in the same site and operated by the same utility.

13 The fuel for fusion typically consists of two isotopes of hydrogen: deuterium and tritium. Deuterium is abundant in nature and not a risk to human health; Tritium must be 'bred' in a reactor and due to its (short-lived) radioactivity it must be carefully managed.

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