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Fusion Before 2050: A net zero future powered by fusion? New possibilities for realising nuclear fusion before 2050

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Highlights

- Harnessing the energy-generating potential of the sun though nuclear fusion has the potential to provide a clean, zero carbon, reliable, and long-term energy source for humanity in the future.
- New and emerging technologies driven by the private sector are increasing the possibility of achieving commercially viable fusion in the next few decades. While not expected to be part of the energy system during this time frame, net energy production could be achieved by 2025 and commercial demonstration by the early 2030s.
- However, key technological barriers remain, specifically in plasma and materials science, tritium breeding and remote maintenance. To address these barriers, the Department for Energy Security and Net Zero should seek increased collaboration with the rapidly innovating private sector, in addition to retaining and strengthening collaborative ties with academic institutions and other international partners.
- The UK is already a leader in fusion technology and strengthening this position could help the country take advantage of fusion's massive potential in the future. A fleet of compact fusion power stations could supply the majority of global electricity and heat for both domestic and industrial purposes in the long term. Additionally, the electricity/heat from fusion power stations can be used to generate synthetic fuel that could be used for non-electrified forms of transport such as shipping and aviation. These synthetic fuels can also be burned to provide heat for industrial processes requiring extremely high temperatures.
- Even if the energy system has already been deeply decarbonised by the time fusion arrives, it can still play an important role in improving grid stability as a carbon neutral source of base load power that, in contrast to nuclear fission, does not produce long-lived radioactive waste.

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Grantham Briefings analyse climate change and environmental research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other publications are available from **www.imperial.ac.uk/grantham/publications**

Introduction

Nuclear fusion, the physical phenomena of fusing atomic nuclei that powers our Sun, has long been heralded as the ultimate terrestrial power source. It differs from nuclear fission, the process of splitting large atoms to release comparatively less energy. Theoretically, nuclear fusion could provide limitless and reliable electricity, heating, and fuel without emitting greenhouse gases (GHGs) or long-lived hazardous radioactive waste. After over 50 years of development, scientists have achieved the capability to generate the sufficiently hot charged gases (plasmas) needed to fuse atomic particles. However, all fusion devices developed to date consume more energy than they produce. This is quantified by the 'fusion gain,' denoted by Q. In order to produce more energy than it consumes, a device would need to achieve a fusion gain greater than 1.

There are two main approaches to generate and confine a fusion plasma: magnetic and inertial confinement. In magnetic confinement, strong magnetic fields trap the constituents of the fusion plasma like a magnetic bottle, while inertial confinement instead employs momentum to achieve the required fusion conditions, for example by imploding a fusion fuel into itself.

Our current best approach is the 'tokamak', a doughnut shaped device that uses magnetic confinement. With this approach, we have achieved a fusion gain of up to $Q = 0.67$ (roughly 70% efficiency – considering the plasma alone). However, this was achieved in the 1990s, and progress in fusion has stalled since.

This paper provides an overview of the current state of fusion development and prospects for the future, including what governments and policymakers can do to enable further technological innovations. It begins with a brief history of our current path to fusion and why progress has stalled. It then discusses recent developments in the private sector, including the 'lean-agile' principle and how governments have responded. Finally, it appraises the current viability of commercial fusion technologically and its potential role in a future low carbon energy market, including recommendations to governments for implementing fusion.

Status of publicly-funded fusion

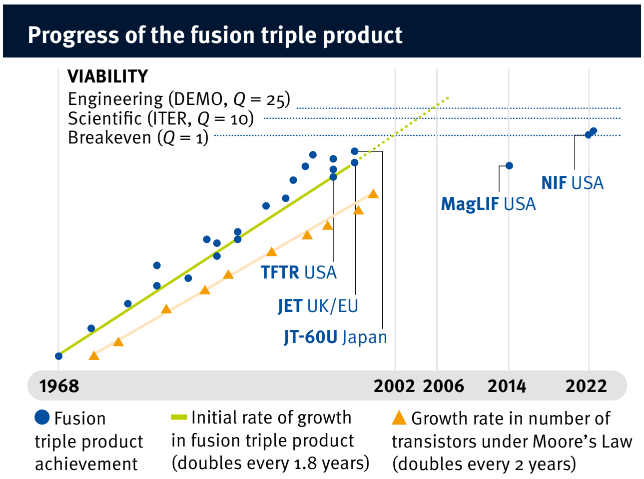
Public institutions have been working on fusion for over half a century. The latest publicly funded device is the International Thermonuclear Experimental Reactor (ITER), currently under construction in France. It is a collaboration between seven international partners – the European Union (EU), Japan, Russia, China, India, South Korea and the United States (US) who are sharing the €220 billion cost. Being a large device, it aims to demonstrate significant energy amplification (a factor of 10, yielding 500 megawatts) by 2035. ITER is expected to achieve this goal, after which it is to be succeeded by the first fully fledged demonstration fusion power stations, from which commercial rollout can proceed. A well known design is the EU's demonstration power station (DEMO) – a larger device than ITER, which aims to deliver around a gigawatt of electricity to the grid (for context, the UK's electrical demand is around 50 gigawatts).

The EU plans to build and operate DEMO by 2050. Given that DEMO will take at least 20 years to build, the first commercial fusion reactors are not expected until after 2070 and therefore, this pathway to fusion will not be of use in reducing GHG emissions in the next three decades.

Why is fusion always '30 years' away?

An inside 'joke' in the fusion sector is the seemingly fixed estimated time to delivery, which hovers between 30 and 50 years. There have been many headlines over the past few decades claiming that fusion will be achieved imminently – and this continues even today.

A useful, simple metric that quantifies our progress towards viable fusion, and the performance of a given fusion device, is the *fusion triple product*, which is a measure of how hot and dense the fusion plasma is, and how long we can sustain (confine) it. If this metric is large enough, the fusion plasma will release more energy than was consumed to generate it, a condition known as breakeven. As the fusion triple product increases further, the fusion plasma becomes self-sustaining and the condition known as *ignition* is realised. Under the conditions of ignition, the heat released by the fusion reactions



Progress of the fusion triple product

Figure 1: Historical progress of the fusion triple product (blue) and transistor number (orange). The green dashed line represents the extrapolation of the initial rate of growth in the fusion triple product ahead in time from the late 1990s. Using values of fusion triple product corresponding to different milestones (breakeven, demonstration plant), the estimated dates of delivery of these milestones are inferred, assuming the maintenance of the initial momentum in fusion triple product.

heats the fusion plasma, such that no additional energy input is needed (in theory).

In practice, a fusion device must be able to produce enough excess energy to offset its cost; and so, a higher fusion triple product is key. Our historical progress according to this figure of merit is illustrated in Figure 1.

As shown in Figure 1, initial progress on fusion in the 1970s was incredibly rapid, in fact faster than Moore's Law – which states that the number of transistors in a microchip doubles roughly every two years. During this time, it was not unfeasible to claim that fusion would become a reality in the near future, and indeed, it was during this era of rapid progress that the now ironic headline of fusion being 'only 30 years away' became endemic. At the turn of the millennium however, the fusion triple product reached a plateau, coinciding with the beginning of ITER's construction. If the initial rate of progress had continued, a device with a performance akin to ITER would have been in operation by around 2005. A similar story exists for a DEMO-like device (at least in performance).

MagLIF and NIF are laser-based devices (implementing inertial confinement). Although promising in performance when considering the fusion plasma alone, these types of devices are extremely inefficient compared to non-laser based methods when accounting for the entire system (~ 10% efficient[1]), and will require significantly greater performance (fusion gain) in order to offset their higher input power requirements. This is mainly due to the innefficiency of high-power lasers (~ 1%).

However, when considering the fusion plasma alone (disregarding the inefficient nature of the overall system), NIF is shown to be the current leader in fusion triple product (achieved in December 2022). In fact, NIF has surpassed even the point of breakeven, achieving Q = 1.54. In this region, the plasma becomes self-heated by the alpha particles (helium nuclei without electrons) generated by the fusion reactions, as the heat provided by these alpha particles outweighs the heat losses by radiation and conduction[1] – i.e. ignition.

Temperatures in excess of 100 million degrees Celsius are required to achieve sensible fusion gain ($Q > 1$), which have not yet been achieved by MagLIF (around 20 million degrees celsius). These temperatures have been achieved in some tokamaks and NIF, yielding the hottest artificial plasmas, with temperatures in excess of 150 million degrees celsius (ten times hotter than the core of the Sun).[2]

Prospects were much brighter in the past. Almost half a century ago in 1976, the Tokamak Fusion Test Reactor (TFTR) in the US intended to 'demonstrate deuterium-tritium (D-T) fusion energy production' (energy production through the fusion of deuterium and tritium fuel, two isotopes of hydrogen).[3, 4] A similar objective was held by the EU's Joint European Torus (JET) and Japan's JT-60U.[3] However, these devices never achieved their objectives due to newly-discovered phenomena detrimental to their performance, including plasma disruptions, instability, and turbulence. These issues affected the performance of JET, JT-60U and TFTR and they performed significantly below the point of breakeven, a key reason why fusion was not realised at that time. To overcome these issues, it was understood that device size would need to increase. This 'build bigger' approach has culminated in the ITER megaproject, which is late in its delivery and over budget[5] (an expected feature of megaprojects[6]). This is why the growth in the fusion triple product has stalled since the millennium and continues to stall today. The long lead time to ITER is not an issue so long as the performance improvement it brings correlates with the projected trend, but this is not the case (as explained previously).

This loss of initial momentum is not unique to fusion, with the semiconductor industry facing a similar issue due to the physical limits of transistors approaching the size of atoms.[7] Although progress in fusion was initially highly promising, leading to the expectation of fusion within '30 years' at the time, the unforeseen discovery of new phenomena detrimental to plasma stability stalled progress. Thus, today, fusion is still seen as '30 years' away.

Accelerating development

The COVID-19 pandemic has hindered the ITER-DEMO pathway to fusion, delaying implementation towards the end of this century. For example, social distancing, reduced capacity, self-isolation and the closure of facilities (labs) all have inhibited operations in the fusion industry.

In addition, the UK's departure from the EU has changed the way it engages with other countries and the real effects on research collaborations will not be known for some time. In the past, the UK has benefitted immensely from research collaboration with the EU. For instance, JET, the most efficient tokamak in the world ($Q \sim 0.7$), is an EU project and European nuclear collaboration is headed under the Euratom organisation, which the UK has now left, potentially impeding collaborative fusion research. Additionally, the combined effect of Brexit (changes to the way the UK trades with the EU) and the pandemic significantly impacted supply chains, including those depended on by the fusion sector (e.g., materials).

During the Brexit negotiations, an agreement was struck between the UK government, the UK Atomic Energy Authority (UKAEA), the EU and Euratom, in which a pathway for the UK to rejoin Euratom as an associate member was provided.[8] However, in September 2023, the UK government announced that it will not re-join Euratom and will launch its own Fusion Futures Programme instead.[9]

For a commercial fusion power station to be feasible within the next three decades, device performance needs to improve significantly. Given that fusion power scales with device size, such rapid improvement initially appears unfeasible since ITER has stalled, and building such a device takes a considerable amount of time and money. This pace of change seems unlikely, even if a similar project was picked up by a new, capable entity (e.g., China). However, new and emerging methods to improve the performance of fusion devices aside from ‘building bigger’ are being explored. Given that fusion, if and when proven to be commercially viable, is expected to be a trillion-pound industry, there is a lot of investment interest in promising solutions. Approaches to fusion that afford significant performance improvements (and thus size and cost reduction) are likely to become extremely lucrative, hence the recent explosion in private fusion companies. The private global fusion industry has received over $4.5 billion in private investment (according to the Fusion Industry Association), with investment growing rapidly.[10]

The alternative, ‘faster’ ways to fusion purported by these companies are very aggressive in their timelines, with several companies aiming to demonstrate fusion gain in 2025 and operate demonstration power plants by 2030[5] (significantly sooner than the dates for the ITER and DEMO projects, 2035 and 2050 respectively). Some companies are tweaking the tokamak design, while others are pursuing entirely novel approaches.

The spherical tokamak

One way to improve the performance of the well understood tokamak design is to slightly tweak its shape by reducing its aspect ratio. Conventional tokamaks such as JET and ITER have a doughnut-like shape, whereas spherical tokamaks are more like cored apples (both shown in Figure 2). A reduction in aspect ratio translates to significant enhancements in device performance (up to 3-fold[11]), which then in principle reduce the device size. However, we have been building and operating spherical tokamaks since the 1990s so why was this higher-performing design not used for ITER?

There are two main reasons. Firstly, spherical tokamaks were not as well understood in the early 2000s when ITER was being designed, so the conventional, better understood geometry was favoured. Secondly, there is limited space available in the central column in the spherical tokamak design (akin to the core of an apple). Fusion reactions generate high energy neutral particles (neutrons), which bombard, heat up and damage reactor materials, including those in the central column. A key feature of the tokamak is the central solenoid – a winding of electrically conductive material used to induce a current to heat the fusion plasmas. In all cases, the central solenoid needs to be cooled sufficiently to become ‘superconducting’ (close to -273 °C; explained further in the next section). However, for high performance spherical tokamaks, the increased heat and radiation loads on the central column exceed what can be feasibly cooled. This would typically be resolved by employing more shielding materials (to mitigate the heat and radiation loads); however, in the spherical geometry, the amount of shielding required exceeds the space available.[13, 14] On the other hand, the conventional geometry (as in ITER) has more than sufficient space for adequate shielding and cooling of the central column.

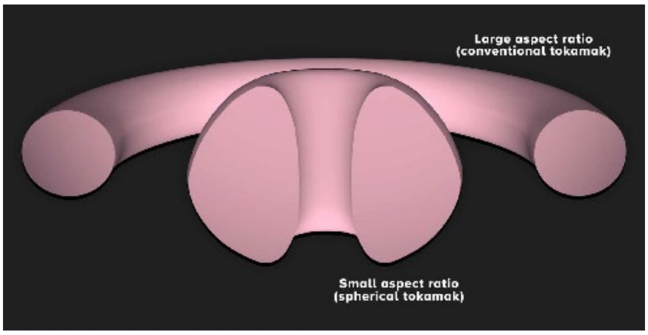


Figure 2: Spherical versus conventional tokamak geometries[12]

High temperature superconductors

Another way to improve device performance, at least in magnetic confinement approaches, is to increase the magnetic field strength. Typical copper magnets (classified as ‘resistive’ magnets) exhibit electrical resistance, and so when a current is passed through them to generate a magnetic field, a large proportion of energy is lost as heat. To prevent these losses, superconducting magnets are preferred, as they exhibit near-zero electrical resistance, significantly reducing energy consumption, enabling the use of higher currents and yielding stronger magnetic fields. The performance of a superconductor is determined in part by the types of materials used. For example, the materials used for ITER’s superconducting magnets (niobium, tin and titanium) become superconducting when cooled to -269 °C (4 degrees above absolute zero); achieved by cooling with liquid helium. This operating temperature has led these types of magnets to be known as ‘low temperature superconductors’ (LTS), as they typically cannot operate above -269 °C.

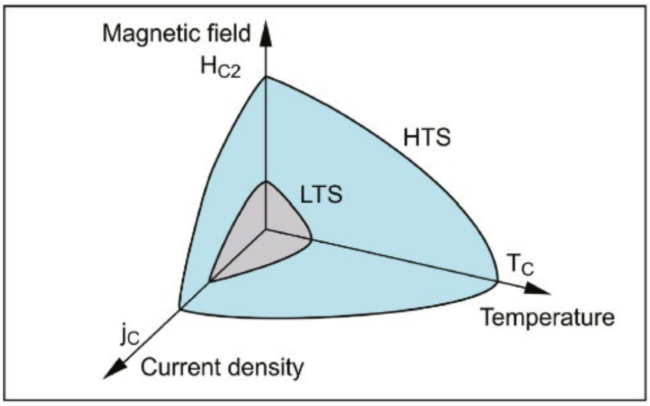


Figure 3: Operating envelopes of low and high temperature superconductors (temperature, current density and magnetic field strength)[15]

The ITER design was finalised around two decades ago, and it was a decade after this that a new class of superconductor, the high temperature superconductor (HTS), began large-scale manufacture. Although classified as 'high temperature', this new class of superconductors (e.g., rare earth barium copper oxide, REBCO) typically operate at around 30 degrees above absolute zero (-243 °C), and so the definition instead relates to them operating at higher temperatures relative to LTS magnets. A higher operating temperature has several advantages. Firstly, it reduces the cost and size of the cryogenic system – ITER's cryogenic solution constitutes a quarter of the device cost and a significant proportion of the land footprint. Secondly, it makes the high performance, compact spherical tokamak concept much more viable, as the shielding requirements are reduced, allowing for a slimmer central column. Thirdly, HTS magnets can carry more current, and thus induce stronger magnetic fields (these operating envelopes are represented visually in Figure 3).

An increase in magnetic field strength translates to enhanced performance. For example, Commonwealth Fusion Systems, in collaboration with MIT, plan to build a conventionally shaped (doughnut) tokamak with HTS magnets, named SPARC (shown below). This device is roughly half the size of JET but performs more than twice as well (fusion gain of 2 versus the 0.7 of JET; major radii 1.65 metres versus 6 metres). In fact, these performance numbers for SPARC are quite conservative, with a recent expert peer-review finding that SPARC could achieve a fusion gain of up to 10 – a similar performance to that planned for ITER, a device that is 10 times larger.[16] Hence, HTS technology alone can afford up to a ten-fold reduction in device size when compared to LTS technology. SPARC is to be succeeded by the planned Affordable, Robust, Compact (ARC) reactor, a device of a similar size to JET (roughly 6 metres), that aims to yield around 200 megawatts of electricity (fusion gain around 10).[17] The current target for operation is 2030.

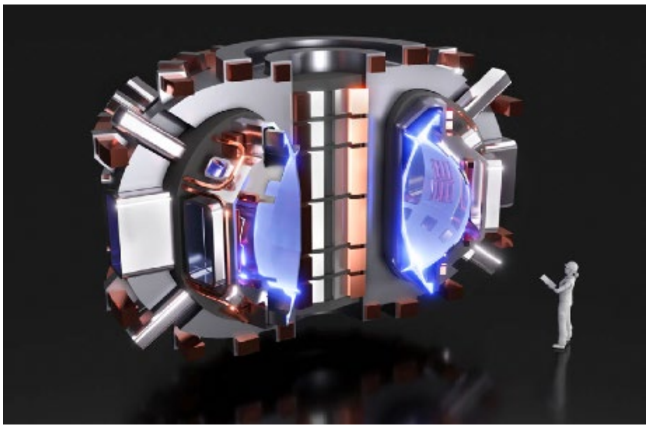


Figure 4: Rendering of SPARC, a conventional (doughnut-shaped) tokamak which employs high temperature superconducting magnets aiming to demonstrate a fusion gain of at least 2 in 2025[16]

These performance improvements are only built upon when the aspect ratio is reduced and the tokamak becomes more spherical in shape (as mentioned, HTS technology mitigates the issue of the slim central column in the spherical geometry). Efforts are being made in the private sector to demonstrate fusion gain with this synergistic design.[11]

Lean-agile practices

As described above, increasing the magnetic field strength and using a more efficient geometry can enable significant reductions in device size and cost and, by extension, construction time, potentially opening up a faster way to fusion.[18] Some companies are pursuing very aggressive timelines – fusion gain by 2025, power plant operation at the end of this decade – and represent a significant acceleration in the development of fusion energy compared to the historic public sector effort. Technology is a key enabler of this recent shift in the fusion field – there is now an ongoing global race to operate the first fusion device that is a net producer of energy.

These aggressive timelines exemplify the short iteration times enabled by size reduction, which in turn has been enabled by the application of new technologies. This kind of rapid iteration is a key feature of the lean-agile ethos, in which costs (materials, money, time) are kept to a minimum in order to enable rapid progress towards a desired goal. The merits of this philosophy have been realised in the space sector[19] without compromising safety.[20] There is an increasing possibility that private companies could achieve similar feats in the fusion sector (safe fusion, cheaper, sooner), and indeed they have already made substantial progress towards their goals.

Public sector response to private advances

The disruption instigated by the burgeoning private fusion sector has forced the public sector to reappraise the ITER-DEMO pathway. For instance, the US National Academies of Science, Technology and Medicine now support cheaper, faster ways to fusion; urging the US government to '[remove] the barriers to low-cost fusion development'.[18] However, commercial fusion reactors must work with 'burning' ($Q > 1$) plasmas, which have only recently been generated in lab conditions (NIF, 2022 – an inertial confinement device). If the US left the ITER project, they would have to develop this capability themselves (at least with respect to a magnetic confinement approach); a wasteful investment of time and resources when their involvement in the ITER project, which is nearing completion, will provide just this, at a significantly lower cost than if they pursued such a project alone. Furthermore, the US wants their researchers to work on ITER to gain first-hand experience, as opposed to ostracising themselves from the international fusion community and having to study the research outputs from the outside – a situation that could result in the US being left behind in fusion. This position allows the the country to leverage ITER, no matter what happens.

The US is now aiming to build a demonstration fusion power plant,[21] expected to operate in 2040,[22] whilst also working closely with private fusion companies. Although small in comparison, private fusion companies are still able to pursue cutting edge research through public-private collaboration. In addition to the already existing collaboration between private companies and academic institutions, the US Department of Energy (DoE) has created the Innovation Network for Fusion Energy (INFUSE) program, which in essence, provides private fusion companies with resources they need, such as access to national research labs to solve the remaining technological challenges they face. Through INFUSE, private companies can be awarded up to $500,000, and only have to contribute a fifth of the project cost. 40 Grants have been awarded to a plethora of private fusion companies (value $9.93 million[23]). The National Academies recommended that these private companies, in collaboration with the DoE and academics, develop several pilot plant designs.[21]

In the UK, ITER is to be used to inform the design of the Spherical Tokamak for Energy Production (STEP), a £2 billion pilot fusion power station, £222 million of which the UK government has currently pledged, aiming to operate by 2040. STEP will have a major radius of 5 metres and aims to deliver 50 megawatts of fusion power to the grid. Although demonstrating the delivery of fusion energy to the grid, STEP does not integrate a fuel breeding system. Fusion reactors must generate their own fusion fuel, tritium – a shortlived radioactive isotope of hydrogen – as it is in scarce supply.[24] Tritium self-sufficiency is a required capability of a commercial fusion power station, and has not yet been demonstrated, although this is one of the objectives of ITER. The final costings and design (and potentially scope – namely tritium breeding) for STEP may change during the course of its development in the coming years.

STEP, being a spherical tokamak, is subject to the design challenges of shielding and cooling of the central column as discussed earlier. The UKAEA's previous three spherical tokamaks (START, MAST and MAST-U) all used resistive copper magnets, which are perfectly sufficient for research purposes. However, for an operating power plant, superconducting technology is essential. There are two choices: LTS or HTS technology. As noted previously, high performance LTS spherical tokamaks do not exist because it is a challenging design in principle. However, although HTS resolves these issues, it introduces several new challenges – it is a much younger technology, and thus needs a lot of development to implement. The UKAEA is now collaborating with Commonwealth Fusion Systems to develop and integrate the newer HTS technology into STEP.[25]

Where private sector firms, such as Commonwealth Fusion Systems and Tokamak Energy have the advantage of HTS technology, the UKAEA has the advantage of their new £45 million cutting edge spherical tokamak (MAST-U), which will inform the design of STEP and help solve some of the remaining challenges to fusion. One such challenge which MAST-U aims to solve is the heat exhaust problem, as demonstrated by MAST-U's novel Super-X divertor. The UKAEA claims a ten-fold reduction in heat load is achievable.[26] In fact, this solution is now to be implemented into ITER. The UKAEA is sensibly leveraging their expertise and rich experience with spherical tokamaks, enabling them to pursue the previously unfeasible high performance LTS spherical tokamak design.

Demonstrating net fusion gain is only part of the puzzle. A commercial fusion plant represents the integration of several high-level technologies – superconducting magnets, materials that can tolerate extreme conditions of heat and radiation whilst being remotely replaceable, and tritium breeding and processing. Although STEP does not intend to integrate the tritium breeding aspect of a fusion plant, the UKAEA has been granted £184 million from the UK government to develop into a global hub for fusion technology, tasked with working on the remaining challenges to commercial fusion:

- Develop fusion materials (Materials Research Facility, MRF)
- Validate fusion reactor component performance (Fusion Technology Test Facilities, FTF)
- Tritium handling (Hydrogen-3 Advanced Technology, H3AT)
- Remote maintenance (Remote Applications in Challenging Environments, RACE)

Thus, the UKAEA is definitely poised with STEP to demonstrate the required integration of all the technologies for commercial fusion. Small, private companies alone cannot compete in this regard, nor do they necessarily need to in order to succeed commercially.

The UK, whose academic institutions have been working with private fusion companies for some time, is also starting to see increasing government collaboration with the private sector. In 2021, the UKEA launched the Fusion Industry Programme (FIP) to 'accelerate the growth of the UK's fusion industry'. The programme will award £23 million over the period of 2022-2025 and over 58 organisations are already being awarded projects.[27] This work intends to support the development of STEP, which has been sited in West Burton, Nottinghamshire at an old coal-fired power station, allowing STEP to make use of the generators and facilities already present there.[27] This value is on top of the £103m already awarded by government,[27] with more funding sought by UKAEA in the coming years. Globally, over $6 billion has currently invested in the private fusion industry.[28]

Additionally, the UKAEA has agreed to host the Fusion Demonstration Plant of the Canadian private company General Fusion on its Culham campus. The plant is expected to be fully

Figure 5: Rendering of Fusion Demonstration Plant (General Fusion), sited at the UKAEA campus, intending to operate in 2025[30]

operational by 2027.[29] This is an excellent opportunity for both parties, who will reap the experience of designing, supplying, constructing and operating a pilot scale plant.[31]

General Fusion employs magnetised target fusion, in which a plasma core is compressed by the pneumatic injection of molten metal to generate fusion conditions. This approach is advantageous in that the issue of radiation damage is eliminated by the use of a liquid 'blanket', which is then used to heat water and drive a steam turbine to generate electricity. As of current, they have demonstrated plasma compression in sub-scale devices, and have not yet attained the required conditions for fusion.[32]

Elsewhere internationally, further fusion pilot plants are currently being planned. The EU intends to follow up from ITER with DEMO in 2055. China is pursuing the China Fusion Engineering Test Reactor (CFETR), aiming to operate in the 2030s.[33] Korea aims to construct their demonstration plant, K-DEMO, by 2037.[34] Russia is currently pursuing a hybrid fusion-fission approach with the DEMO Fusion Neutron Source (DEMO-FNS) planned for construction in 2033.[35] The fusion neutrons in DEMO-FNS are intended to be used to burn up long-lived fission waste and breed new fission fuel from uranium.[36] Japan intends to begin construction on their demonstration plant, JA DEMO, in 2035, whilst India also has aspirations to begin construction on their own demonstration plant in 2037.[37]

Overall, it is seen that most wealthy countries are pursuing fusion demonstration plants, timed strategically to deploy after the D-T operations of ITER in 2035. Significant public-private collaboration has so far only occurred in the US and UK.

How ready is fusion for deployment and use?

The recent surge of investment in the private fusion sector has generated a lot of excitement. There are new technologies and approaches enabling development to accelerate,[38] but significant challenges remain. Historically, scientists have been in this position before; close to solving fusion, only for a series of new challenges to present themselves shortly thereafter. There has been significant progress on tackling these issues and better controlling fusion plasmas, whilst additional data and experience has reduced uncertainties in expected device performance through the development of scaling laws. However, burning (i.e., self-heating) plasmas represent another newly-accessible domain which may reveal unforseen challenges.

Even if burning plasmas are not too troublesome to work with, there is still significant work that needs to be done to get to the point of commercial deployment. Currently, fusion is limited by technological capability. Technological progress is measured by Technology Readiness Level (TRL), which ranges from 1 to 9. A newly observed phenomenon being reported in the scientific literature (e.g., the original discovery of high temperature superconductors in the late 1980s) corresponds to a TRL of 1.[39] On the other hand, a TRL of 9 represents something that is fully implemented, such as your car. As shown in Figure 6, fusion is currently at a TRL of 3-4, with research taking place in national laboratories and industrial parks, as opposed to operating demonstration pilot fusion plants. ITER-like devices (demonstrating net fusion gain) will deliver a TRL of 5, beyond which a full integration of the required technologies is required to reach a TRL of 6 – from which commercial rollout begins. Under this definition, STEP – although a field-scale net-gain fusion power plant – is limited to a TRL of 5, as it does not integrate all the required capabilities of a commercial fusion power plant (specifically a closed tritium fuel cycle).

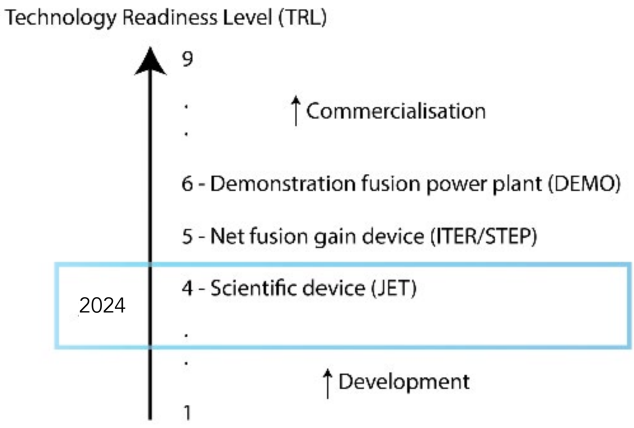


Figure 6: Technology readiness level of fusion

In order for fusion to make a meaningful contribution to decarbonisation in the next three decades, technology must reach a TRL level of at least 6 within the next decade. The US Fusion Energy Sciences Advisory Committee was tasked with identifying transformative enabling capabilities (TECs) that could enable the US to deliver fusion technologies more rapidly. They identified several TECs: using AI to better control fusion, high temperature superconductors (see Section 7), advanced materials and manufacturing for more resilient plasma facing components, and several new innovations that will aid in enabling tritium self-sufficiency. Moreover, they found using liquid-metal for plasma facing components (a solution which in effect gets rid of the radiation damage problem) to be a promising TEC.[40] This approach is being considered by several private sector companies, such as Commonwealth Fusion, General Fusion and Tokamak Energy.

While the technological challenges remain immense, the recent exponential growth in private-sector fusion brings new advantages such as lean-agile systems, competition and innovation. For now, expectations are high, even though significant uncertainty remains. This uncertainty may be temporary, if the first demonstration of controlled net fusion is achieved by 2025. Assuming that happens, it is likely that we will see the demonstration of a minimum viable product (i.e., TRL 6) shortly after (e.g., 2030 for Tokamak Energy's ST-E1[41]). If these fail or are delayed, there are other independent programs that will be able to pick up the slack (e.g., ITER, STEP), with a 2035-2040 deployment date still allowing meaningful contribution to decarbonisation.[22]

Although smaller and more powerful fusion devices will be cheaper and quicker to implement, they will generate more energy in a smaller amount of space, creating very intense conditions that would need frequent shutdown and remote maintenance. Hence, an engineering limit exists. To resolve it, significant work is needed to develop more tolerant materials that can withstand the more intense conditions and enable reasonable plant availability. Plant availability, in the context of electricity generation, is a measure of the percentage of time that a power station is 'up', generating electricty and delivering it to the grid. Future fusion power stations will not be feasible – both economically and from the perspective of grid stability – if they necessitate frequent and long maintenance periods. Development of materials more tolerant to radiation damage reduces the frequency of maintenance interruptions, whereas holistic, modular design approaches combined with cutting edge robotics intends to help reduce the length of time required to complete a successful maintenance operation.

Commercialisation and limitations

Being able to generate net energy using nuclear fusion, once achieved, can only aid the decarbonisation effort under two conditions. Firstly, there must be a demand for it. Secondly, it must be cost competitive. Following the historical, 'large' approach (ITER, DEMO) to fusion, even if commercialised, will yield dispatchable base-load generation akin to gigawattscale fission power plants today. Given that fusion does not generate long lived radioactive[17] waste, and is relatively safe, these large fusion power stations would be excellent in a carbon neutral energy network. However, there is not enough material available to build a global fleet of them.[35, 36] Size reduction is incredibly useful in this regard – as smaller reactors need less rare earth metals to build, and are more economically viable.[11] The traditional, ITER-like tokamak is not expected to be cost-competitive in a future market where renewable sources are expected to only get cheaper.[41] Given the variability of renewable generation and insufficient energy storage capacity, there is a need for low-carbon dispatchable base load generation (nuclear), and thus there is a market for cost competitive fusion. However, as mentioned previously, the timing of deployment is critical since, via the larger and slower route to fusion, commercial deployment will arrive near or after a time at which net zero is aimed to be achieved – nullifying the demand.

Even if fusion cannot penetrate the electricity market, electricity currently constitutes only 20% of UK carbon emissions. The remainder lies in heat and transport, which constitute 40% each. Not only are these immensely large sources of carbon emissions, but they are also incredibly difficult to decarbonise. Luckily, fusion could potentially eliminate emissions from these sources through 'cogeneration'. The implementation is largely like the fission approach,[42] in that small modular reactors (SMRs) enable distributed generation and thus district heating using the otherwise wasted heat in the thermodynamic cycle. The heat can also be siphoned off for use in industrial processes, although some processes use temperatures in excess of what can be safely supplied from any power station (above 1000 °C), and so in practice this limits fusion to covering around 90% of the industrial heat demand. In terms of transport, the heat or electricity from a fusion plant can be used to generate synthetic kerosene for air transport, in addition to hydrogen and ammonia (if there is a demand for them in future). SMRs can also be more economically advantageous than centralised, largescale generation; assuming economies of scale (mass production) can be realised. It should also be noted that electricity demand is only expected to increase in future, as electrification of the energy system proceeds (e.g., full electrification of small road vehicles) – providing increased oppurtunity for fusion.

A fleet of modular reactors offers more load following flexibility compared to a single large plant, although still not as rapid as gas peaking plants, useful in a future energy market that includes more variable renewables. This flexibility can be achieved by turning off some reactors (e.g., for maintenance), or diverting the output of a given fusion reactor to different demands (e.g., electricity, heat, hydrogen). This idea is good in principle, although the implementation is quite involved, requiring firstly the infrastructure to enable capability – i.e., the installation of a district heating system; hydrogen production and storage facilities, and secondly coordination and planning between the various energy demands.
Some solutions are available, for example hydrogen production would be a good sink for excess supply, however sufficient storage will need to be made available. Given the bias towards capital costs for e.g., rare earth metals, superconducting magnets, vacuum vessel, containment facility and cryoplant, fusion plants will need to maximise plant availability (defined earlier) to drive down costs. It is expected that natural gas and carbon capture and storage (CCS) will need to be used in future (post-2050) for peaking plants and the remaining 10% of industrial heat demand that cannot be met by nuclear.

With regards to waste, some teething issues lie ahead for fusion. Although it does not generate long-lived radioactive waste like fission, it does generate radioactive waste that is more hazardous but for a significantly shorter amount of time (no more than a century compared to hundreds of thousands of years for fission waste). Some of this waste (radioactive steel) could be so active as to be classified as an intermediate level waste, a classification that requires deep geological storage by the UK and EU regulators. If fusion is to necessitate an expensive geological disposal facility, then it faces the same waste problem as fission.[41] However, this fusion waste is much less volatile compared to the trapped radioactive gases in fission waste, and so should not require such deep storage to safely isolate it from the biosphere. Further efforts are needed to validate the safety case of near-surface storage of fusion waste in order to satisfy the concerns of the public. Another point of contention lies in a certain type of steel (Eurofer) that is intended to be used in DEMO. This material does exhibit long-lived radioactivity, however we are not committed to use it, and better alternatives should be sought.

In order to build and operate a commercial fusion power plant, it must be approved by the appropriate regulator – a process that takes time. The nuclear sector is used to a holistic approach due to the need for decommissioning, and fusion is similar in this regard. Hence, work is already being done on developing the regulation and safety cases for future fusion power plants to get a head start with the regulator, in addition to prospectively informing ongoing designs.[43] In terms of licensing, the UKAEA research campus is not classified as a nuclear licensed site, and it is hoped that STEP too can avoid this hurdle entirely – thus streamlining the process somewhat. Indeed, government appears keen to develop a new regulatory framework for fusion, which is expected to be less involved than that for fission whilst retaining standards. Government and the regulator should be mindful of these teething issues and resolve them rapidly such that the UK can better capitalise on the emerging international fusion market.

Conclusion

Nuclear fusion, although a great scientific and engineering challenge, is a technology that has the potential to help sustain a long-term zero-carbon economy in the future. Recent technological advances and experience have opened new, faster ways to commercial fusion which may enable fusion to contribute to the long-term decarbonisation effort. A burgeoning private fusion sector intends to capitalise on these rapid developments, aiming to demonstrate net controlled fusion gain by 2025, and grid-ready fusion power by 2030. These audacious goals are grounded in some truth, following validation of leading technology experts. In response to this, international governments are now pursuing their own demonstration fusion power stations, aiming to operate in the 2040s.

The current key challenge to fusion is technology. Intense efforts are underway e.g., public-private collaboration to solve the remaining technological challenges. However, until the key milestones are demonstrated for net fusion energy, and a field-scale prototype is operated uncertainty remains. Regardless, government and regulators should keep a close eye on fusion in the coming years and be ready to facilitate commercial rollout once it arrives. Tackling climate change requires a holistic approach, and so the more tools we have at our disposal the better. Fusion is most definitely a useful tool in this regard, and once demonstrated will integrate extremely well into the future energy system.

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