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The Promise of Magnetic Fusion for a Sustainable Future

Techno-Sustainability Series – 1

Abstract:

Using nuclear fusion technology to produce clean energy is a way to improve the transition toward a sustainable economy in Europe, generating large-scale, carbon-free energy. Not only is it an important scientific and technological achievement, but it is also more efficient than all other forms of (clean) energy production.

Without claiming to be exhaustive, this paper aims to introduce the concept of fusion technology, providing an overview of the current achievements and regulatory framework in the EU, and highlighting the relevant stakeholders and projects that can potentially lead to future large-scale implementation of this technology as part of the EU sustainable transition.

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Executive Summary

The EU's plan to move towards achieving net-zero levels of emissions in the next 30 years needs bold economic and industrial policies, which were put forward in the Commission's 'Fit for 55' package (FF55). The FF55 is ambitious and necessary, but it comes with costly trade-offs and many checkpoints down the road toward 'greening' our future. Whereas the 'green' agenda only offers a single path, trust in the role of technology and innovation is needed for Europe to be open to new and perhaps unforeseen ways forward for economic and human development. Instead of a narrow, unbending, and dogmatic approach, it is time for us to recognise the many roads to a net-zero future.

Seeking a sustainable future without a strategy for engaging cutting-edge technologies would be a risk, both to investments and Europe's strategic autonomy. Meanwhile, EU Member States' joint effort to bring together technologies, knowledge, and resources to achieve a techno-sustainable future will contribute to a better tomorrow. It will enable us to take advantage of the fourth industrial revolution with its technological advancements and translate them into a concrete sustainability project providing technological and market-based solutions to environmental problems.

The ELF's Techno-Sustainability Series is built on the assumption that technology is our ally in tackling climatic and environmental challenges. Existing applications of AI and quantum computing, new generations of networks, and IoT can already help in preventing energy poverty, enhancing energy efficiency in housing, and providing data and information to help achieve better living standards. Moreover, the techno-sustainability connubium will also contribute to creating new business opportunities that could boost the EU's economy. New and existing technologies are the pivotal point around which to construct the whole discussion about sustainability in Europe.

The discussion of nuclear technologies should look ahead, relying on science to support promising projects for the future of energy: nuclear fusion. The research in this field and the recent successes of various projects in which Europe is involved must be followed closely. Looking ahead to 2050, one cannot but think of the opportunities offered by this technology. Despite being currently at an early stage, it could represent a solution (if not 'the' solution) to the energy supply problems of the future. Even though magnetic fusion is still far from being implementable on a sufficiently large scale to produce energy, this technology has the potential to completely disrupt the energy market and mark the transition away from fossil fuels.

The necessary element to generate fuel for fusion (lithium and deuterium) can be found almost anywhere in the world in enough quantity for any country to be fuel-independent in a future where fusion power plants will be deployed. Furthermore, these complex power plants integrate hundreds of systems working together, creating a complex value chain that will require highly skilled personnel both for the design and operation of future fusion power plants. Geopolitically, there will be a shift away from fuel reserves as a source of power and money, to a world where access to this highly complex integrated system for fusion technology will be the key. For this, EU institutions need to help encourage research projects and investment in producing highly skilled personnel as a priority.

Policy recommendations

- Europe must welcome R&D projects in fusion technology without raising regulatory barriers, but rather by simplifying and streamlining them.
- EU regulatory power might be of help to better allocate resources representing a best practice on how to balance research projects and commercial deployment of this technology.
- Europe must favour multi-stakeholder and joint research projects in the EU that can solve the challenges related to fusion projects. This will also increase Europe's expertise and experience in the global race to fusion.
- The issue of social acceptance of fusion-based technologies is central. European institutions should communicate the advantages of the implementation of fusion energy and involve citizens in the development and adoption of this game-changing means of energy generation.

The EU has the opportunity to foster the development of a flourishing market based on a different paradigm: the one complementing environmental governance with advanced technological and market-based solutions. This will enable Europe to secure its place not only as a global frontrunner with regard to 'carbon targets' and 'emission crops' but also as a provider of best practices in terms of growth, circularity, and sustainability for our future. Climate goals should be eco-pragmatic and follow a realistic approach towards making our future more sustainable and more prosperous. Instead of a Green Utopia, our climate goals need to be based on a realistic vision for a techno-sustainable future.

Fusion: a potentially disruptive technology

According to the latest Intergovernmental Panel on Climate Change Assessment Report, all countries in the world must act now, otherwise temperatures will inevitably rise much higher than the presently agreed limit of 1.5 degrees by the end of the century (IPCC, 2002). This implies that the use of fossil fuels (coal, oil, and gas) needs to be phased out as quickly as possible, while CO2-free energy sources need to be developed and rolled out in parallel.

Nuclear fusion has the potential to cover a substantial fraction of the future energy mix (Braams & Stott, 2002). Nuclear fusion plants will not emit any CO2 during their operations, the fuel is in practice inexhaustible and widely available, and the fusion process is intrinsically safe, with no chance of meltdowns and all activated reactor materials becoming reusable after 100 to 300 years.

Nuclear fusion is the process that powers the stars, including our sun – the source of all light and life on Earth. In the fusion process, nuclei of light elements (typically hydrogen) are smashed together to form a nucleus of a slightly heavier element (typically helium). In this process, a minute amount of mass is lost as the new nucleus is lighter than the sum of the initial ones. This minute amount of missing mass is converted into an immense amount of energy in accordance with Einstein's famous equation, E = mc2 (energy is equal to mass multiplied by the speed of light squared, which is 90 billion square kilometres per square second).

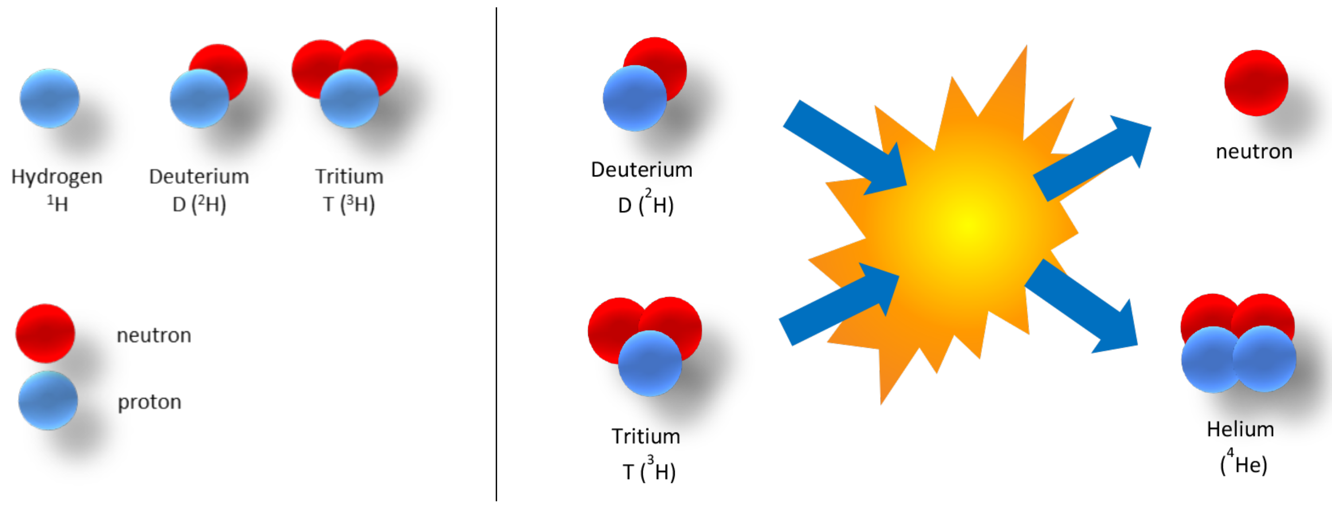
Nuclear fusion is the exact opposite of nuclear fission, in which heavy nuclei (typically uranium, plutonium) are split into lighter nuclei. In the fission process, mass is converted into energy; however, the energy released by a fusion reaction is three to four times greater than the energy released by a fission reaction because the quantity of mass transformed into energy is that much greater.

In the sun and stars, fusion reactions occur at temperatures of about 15 million degrees Celsius thanks to the immense gravitational forces that press the particles close together. To produce fusion reactions on Earth, much higher temperatures, about 150 million degrees Celsius, are needed to compensate for the lower gravity/density of the particles. On Earth, two main techniques are being explored to create fusion reactions. One of them is inertial confinement fusion in which a small pellet of fusion fuel, typically the size of a grain of sand, is irradiated from all sides by powerful laser beams. This simultaneously heats and compresses the pellet to conditions similar to those in the sun and stars, such that fusion can occur. The second more advanced and promising option is magnetic confinement fusion (MCF) in which a dilute gas is heated to temperatures of 150 million degrees. At these high temperatures, all atoms fall apart into positive nuclei and negative electrons; this is called a plasma state – the fourth state of matter. In this state, the turbulent charged particles can be confined using magnetic fields, such that they cannot touch the walls of the surrounding vessel. When the temperatures are high enough, the particles in the plasma can fuse when they collide. In a 'burning plasma', once started the fusion reactions keep providing enough energy back into the plasma that more reactions occur, with the excess energy leaving the plasma captured and used either as heat directly by industry, or to generate electricity. This is what makes MCF so attractive as a future energy technology.

The easiest fusion reaction to achieve on Earth occurs between two isotopes (variants) of hydrogen: deuterium and tritium (see Fig. 1). The nucleus of ordinary hydrogen consists of a single positively charged proton. In deuterium, the nucleus has both a proton and a neutral neutron. Deuterium occurs in nature (every litre of water on Earth contains 33 mg of easily extractable deuterium). Tritium has a proton and two neutrons in the nucleus. Tritium does not occur in large quantities in nature, because every 12.36 years 50 per cent of it decays (breaks down) and is lost. However, this is not a problem, as tritium is produced when the high-energy neutron released by the deuterium-tritium fusion reaction hits a lithium particle in blankets lining the interior wall of the fusion reactor. Therefore, one could say that the fuel of a fusion reactor is made up of deuterium and lithium (one of the most common metals in the world).

Apart from the high temperature, it is important to have a high enough density in the reactor vessel (the more particles, the higher the number of fusion reactions). Additionally, the time taken for the hot plasma to cool, when not being heated, needs to be long enough. Nevertheless, in MCF, the density is typically much lower than atmospheric pressure (the reactor vessel, which has a volume of about 1,000 m3, typically contains at any moment only a few grams of fuel), while the energy confinement time (i.e. the cooling time) is typically in the order of seconds.

Figure 1: On the left: The three isotopes (forms) of hydrogen.
On the right: Fusion reaction between deuterium and tritium yielding helium and a neutron.



Source: EUROfusion (https://www.euro-fusion.org).

Since the fusion process is very efficient, only small amounts of fuel are needed. A working fusion plant delivering 2 GW (gigawatts) of electric power to the grid for a full power year of operation would need only about 500 kilograms of fuel (a fossil fuel power plant needs 4 million times more fuel to generate the same electric power). Half of this fuel is deuterium, and the other half is lithium – the equivalent of nine electric car batteries powering 1.4 to 1.5 million homes for a whole year.[1] Thus, the fuel is essentially inexhaustible. Fusion is also safe, as we will show after explaining the concept of MCF.

For comparison purposes, two GW of fusion power is the equivalent of the power produced by 6.25 million 320-watt solar PV (photo-voltaic) panels or 862 utility-scale 2.32 MW wind turbines (US Department of Energy, 2019). While solar and wind are intermittent and thus require that new and massive electricity storage capabilities be developed and built, nuclear fusion power plants will have a similar uptime to nuclear fission power plants, making them baseload (steady, predictable, controllable) sources of heat and/or electricity.

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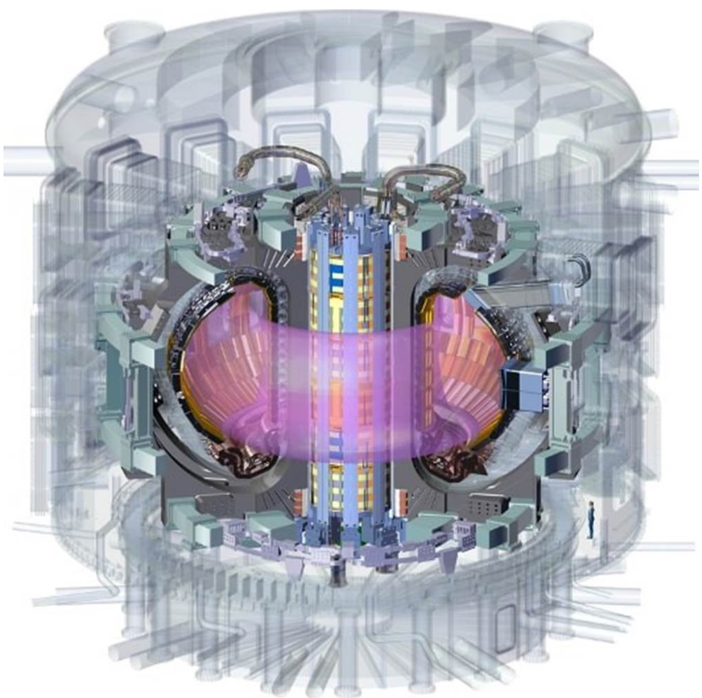
[1] Specifically, fusion reactors need the isotope Lithium-6 is needed, which makes up about 10 per cent of the lithium in a car battery. Most of the lithium is Lithium-7.

Magnetic Confinement Fusion

In MCF, torus-shaped vacuum vessel surrounded by strong magnetic field coils is used (see Fig. 2). Hydrogen gas (ideally a mixture of deuterium and tritium) is heated by various techniques (injection of energetic atoms, and microwave heating) to temperatures of 150 million degrees. At these high temperatures, the atoms fall apart into positive nuclei and negative electrons that are held away from the wall of the vacuum vessel by strong magnetic fields (Braams, Stott, 2002). Once the conditions for fusion are reached (hot enough and dense enough for long enough), the deuterium and tritium fuse into helium and a neutron. The helium is charged and will give its energy via collisions to the other particles in the hot plasma. The neutron has no electric charge and flies out of the magnetic confinement into the surrounding wall, where it will split lithium into helium and tritium, thus generating part of the fuel mix. Additionally, the neutron will heat the wall and, as in conventional power plants, the heat drives turbines that generate electricity.

There are two main types of magnetic confinement devices. The tokamak (see Fig. 2) is the one that is the most advanced in terms of development. In the tokamak, part of the confining magnetic field is generated by inducing a strong current through the plasma; the other part is generated by external magnetic field coils. The second device, called a stellarator, also has a torus shape, but here the magnetic field is completely generated by external magnetic field coils. Although the stellarator has a number of advantages over a tokamak, the design is technically more complex and therefore less advanced.

Figure 2: Picture showing a plasma inside the ITER tokamak.

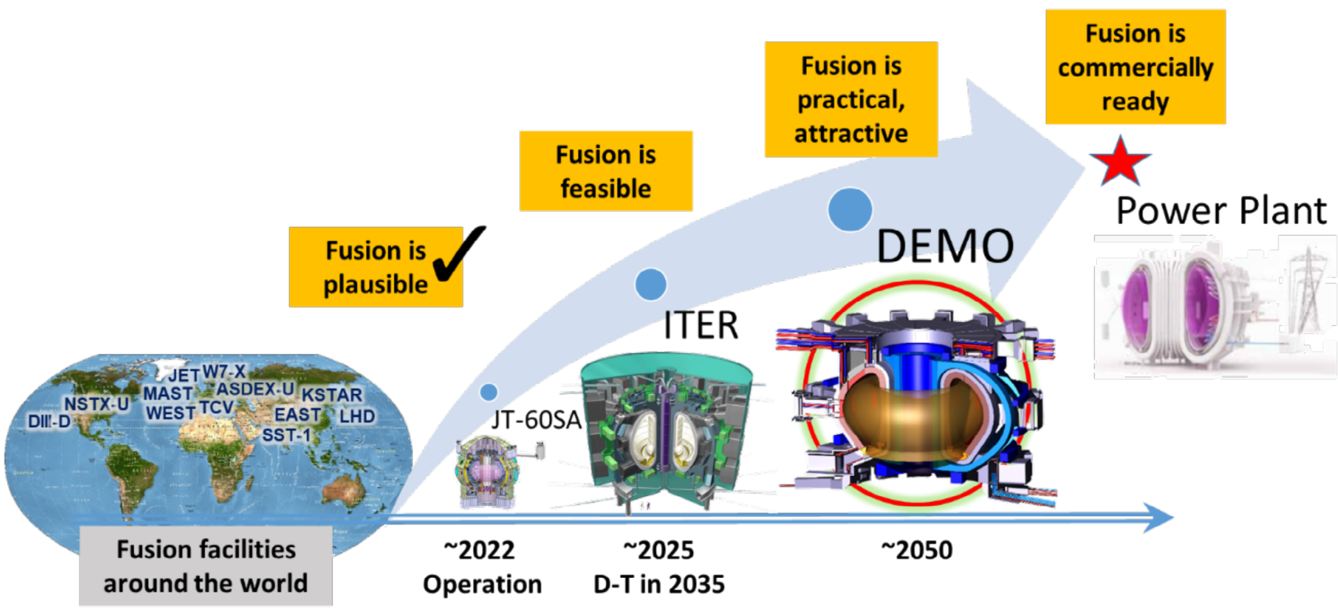


Source: ITER International Organisation [(https://www.iter.org)](https://www.iter.org).

The best fusion energy result ever was reported in February 2022 by the EUROfusion consortium at the Joint European Torus (JET). A total of 59 megajoules of fusion energy was generated in a 5-second pulse using only 170 micrograms (millionths of a gram) of fuel (Banks, 2022). JET is a tokamak device with copper magnetic field coils, and this older magnet technology limits the duration of a high-performance pulse to 5 seconds. Thanks to advanced diagnostics recording what happens every millionth of a second, this was long enough to understand all the detailed processes taking place in the hot plasma. The results have validated the theoretical models predicting that the international ITER experiment, presently being built by China, Europe, India, Japan, Russia, South Korea, and the United States in Southern France, will be able to generate 500 MW (megawatts) of fusion energy using only 50 MW of input energy. This tenfold return on energy within the plasma will be the fusion record that researchers have been waiting decades to achieve.

In short, one can say that JET has shown that fusion electricity is plausible. ITER, which will come into operation in 2025, will demonstrate that fusion electricity is feasible. As an experimental device, ITER will not yet generate electricity, but it will have reactor-grade plasma to test all the technologies that are being developed for a reactor (e.g., tritium breeding). The European demonstration reactor DEMO will for the first time deliver electricity to the grid (Federici et al., 2022). DEMO is presently being designed and should come into operation early in the second half of the century (see Fig. 3).

Figure 3: Simplified European Fusion Roadmap.
Note: Present devices such as JET have shown that fusion is plausible. ITER will demonstrate the feasibility of fusion under reactor conditions and test technological developments. DEMO will generate electricity for the first time.



Source: EUROfusion (https://www.euro-fusion.org).

What are the advantages of fusion, apart from being virtually inexhaustible and CO2-free? Fusion is safe because the reactor operates at well below atmospheric pressure. At any moment during its operation, there are only a few grams of fuel in gaseous/plasma form inside. The fuel needs to be continuously replenished, otherwise the reaction is extinguished. The equivalent of a meltdown in fission reactors is therefore impossible. In the exceptional case that a hole or leak occurs in the reactor, air will stream into the reactor's vacuum chamber and instantly stop the process. The tritium will stay inside the reactor and reactor building, as designed. This inherent safety of fusion power plants means that they could potentially be built close to where the heat and electricity are consumed by industry and cities, significantly reducing the transmission infrastructure required.

Over time, a fusion reactor will become radioactive due to the bombardment of energetic neutrons from the fusion reaction and because reactor materials will absorb small amounts of tritium. Suitable wall materials are being developed that will lose their radioactivity relatively quickly such that after 100 to 300 years the materials can be reused.

Another advantage of fusion is its small geographical footprint. It will not require large land areas, which are desperately needed for food production. Fusion power will be at least 200–400 times more land-efficient than solar, for example.

A final advantage of growing importance is the ubiquity of fusion fuel: it can be found nearly anywhere on the planet in sufficient quantities, so fuel dependency on a few nations will become outdated. This is the truly disruptive aspect of fusion energy: it will create a new world order while enabling humanity to develop potentially without any energy constraints. Fusion can help humanity transition away from fossil fuels completely and permanently, even as energy demands experience accelerated growth (demand is expected to double by 2050, and again by 2100). Fusion energy technology, instead of fuel resources, will therefore be the key to future energy independence for Europe for the next 100,000 years or longer. The opportunities for European industry and skilled workforces, as well as education, will be massive.

What are the remaining challenges?

Fusion researchers have made major progress in recent decades. Aside from the world-record fusion energy achieved in JET, progress has been made in several tokamak devices in Asia in which plasma pulses of more than 1,000 seconds were achieved (Malewar, 2022), albeit not with the same high-energy performance as those in JET.[2]

The long pulses are possible thanks to the fact that these more modern machines are equipped with superconducting coils to generate the magnetic fields (Amelin, 2015). ITER also has superconducting coils and will be able to combine long

[2] They did not use a deuterium-tritium fuel mixture, and while the plasmas lasted a long time, the number of fusion reactions taking place in the plasma was tiny.

pulses with deuterium-tritium fusion performance even higher than that of JET. In principle, it can be stated that, from the physics point of view, scientists are able to currently generate the hot plasmas with a performance close to that of a fusion power plant.

However, there are still a number of technical challenges that need to be resolved. This relates partly to the materials used in the reactor, which need to withstand intense heat loads (similar to those at the surface of the sun) and exposure to high-energy neutrons.[3] Fortunately, the components in a fusion reactor can be actively cooled. Various ideas exist for tritium breeding by splitting lithium in the wall using the neutrons emerging from the fusion reaction, but all of them need to be tested and validated in the so-called Test Blanket Modules in ITER. Additionally, reliable remote maintenance techniques need to be developed that are fast and accurate. Maintenance times in a fusion power plant need to be optimised to keep the downtime as short as possible. There are challenges in developing an adequate nuclear licensing and regulatory system for fusion reactors, as these are completely different from fission reactors. Finally, a skilled workforce and actively involved industry must be promoted.

How is fusion research and technology organised in Europe?

The described challenges and the required effort for developing commercial fusion energy technology are clearly beyond the scope of a single nation, even nations with cutting-edge technological capabilities, skilled workforces, and generous funding. This is why there are joint initiatives at THE international level in fusion research. The European Union is currently contributing to a number of major fusion projects, and in Europe, two main fusion organisations are active.

Fusion for Energy (F4E) was established within the regulatory framework of the European Joint Undertaking for ITER (European Council, 2007). ITER, 'one of the most ambitious energy projects in the world today',[4] is an international collaboration involving hundreds of scientists and engineers from China, the European Union, the United Kingdom (EURATOM, 2021), India, Japan, South Korea, Russia, and the United States (European Commission, 2020b). The project was licensed as a nuclear facility in France in 2012 and it is currently being constructed in Saint-Paul-lès-Durance (France). The ongoing programme and contribution (entrusted to the F4E initiative) is a continuation of the previous Multi-Annual Financial Framework, and the total European financing for this project in Horizon Europe is more than 5.6 billion Euro (based on the ex-ante evaluation) to (European Commission, 2018):

[3] Over the course of a fusion power plant's lifetime, it is calculated that every atom of the reactor materials will be hit by a neutron an incredible 50 times or more.

[4] https://www.iter.org/proj/inafewlines.

> ITER, is an international collaboration involving hundreds of scientists and engineers from China, the European Union, the United Kingdom, India, Japan, South Korea, Russia, and the United States

F4E is also involved in the broader approach wherein they partner with other countries to conduct research together – for instance, a recent partnership for the construction of a JT-60SA experimental tokamak device in Japan.[5]

The other organisation involved in fusion projects is EUROfusion, a consortium of 30 national research laboratories from 28 countries, all brought together under one umbrella to cement European collaboration on fusion research. It oversees and funds all fusion research activities on behalf of the European Commission's Euratom programme, and is guided by the European Roadmap to Fusion Energy – the world's most comprehensive and certain path to realising commercial fusion energy (see Fig. 4). EUROfusion research, which is being done on a range of devices throughout Europe, including the world-record machine JET, is strongly aimed at supporting the ITER research plan. In simple words, EUROfusion's research helps ITER reach its goals in an optimised way (faster and cheaper). EUROfusion is also presently responsible for the conceptual design of the European demonstration reactor DEMO.[6] While ITER aims to demonstrate the production of ten times more energy from the plasma than is needed to heat it (this is called Q-plasma = 10), DEMO aims to demonstrate four times more fusion energy than ITER and deliver a net 500 MW (target) electrical power to the grid.

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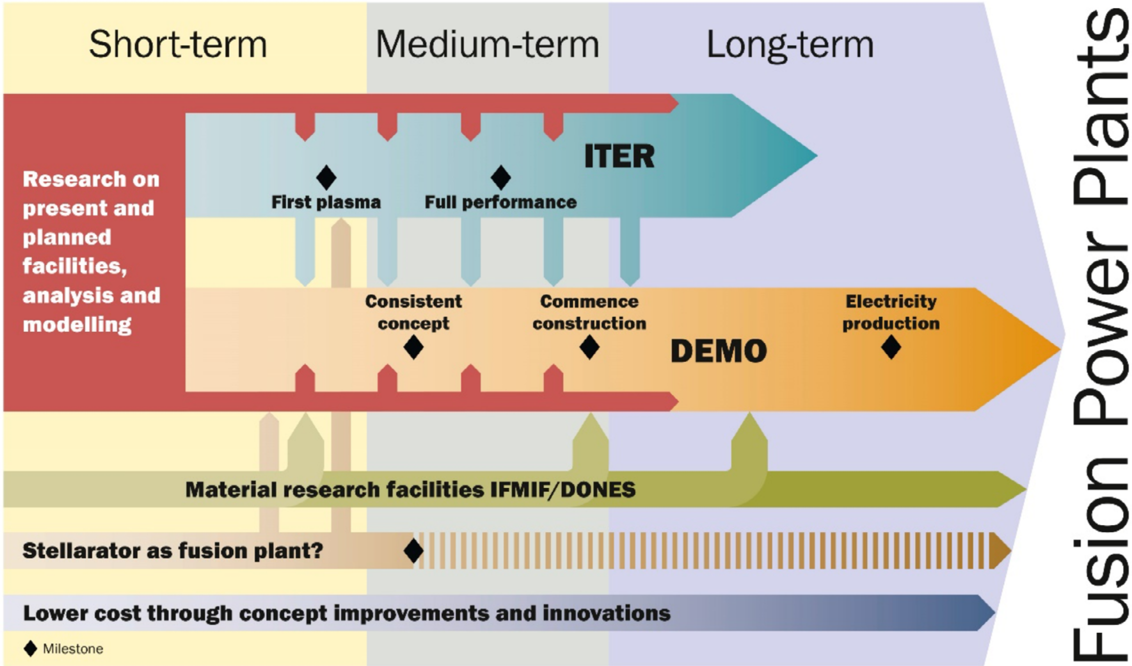
5 For more information about the JT-60SA: https://www.jt60sa.org/wp.

6 After the successful experiment with fusion in ITER, the next step is the establishment and running of DEMO – a facility where fusion will be produced on a large commercial scale.

Figure 4: The European Fusion Roadmap.



Source: EUROfusion
(https://www.euro-fusion.org/eurofusion/roadmap).

The roadmap is centred around ITER and DEMO as central devices and is optimised to tackle all remaining challenges in the shortest possible time. This implies that the conceptual design of DEMO has already started while ITER is still being built. During ITER construction, commissioning and testing, a constant stream of information is flowing into DEMO. Source: EUROfusion.

Innovation and industry competitiveness (technology transfer and spin-offs)

Fusion devices such as JET, ITER and DEMO are Big Science facilities. Companies that are involved in delivering components often need to boost their innovation levels as they need to deliver components that go beyond the state-of-the-art. This has the positive side effect that the companies considerably improve their market potential in other fields. Studies conducted by various Big Science organisations such as the European Organization for Nuclear Research (CERN) and the European Space Agency have concluded that the spin-off market is on average three larger times the original market.[7]

[7] F4E states on their website (https://fusionforenergy.europa.eu) that €5.1 billion has been invested in companies and R&D organisations, 40,000 job years have been created between 2009 and 2017 and another 83,000 will be created by 2030.

In this way, spin-offs from fusion technology have led to completely new, and sometimes significantly large markets (EUROfusion, 2017). For instance, in the area of superconducting magnet technology, a company that worked on the prototype coils for ITER has become the world leader in the field of medical resonance imaging (MRI) equipment with a turnover of approximately €1.5 billion per year. The cockpit of the Airbus A380 is produced by explosive forming of metal plates, a technology originally developed for ITER. So the gains companies make are not limited to delivering on orders for components of future fusion reactors, but also in the continuous spin-offs, which generate profits on a much faster time scale with greater upside potential. Being involved in Big Science in general, and fusion in particular, has enormous benefits for Europe's industrial competitiveness.

European projects for ITER are awarded and carried out through specific calls for tenders that entrust companies with the construction of parts or sections of the ITER experiment. This ensures high-quality outcomes while involving companies from different European regions. It can be said that the overall advancement of this technology is thus the result of a shared effort in creating consistency between different areas of expertise, projects, and experiments, in several locations, in Europe and elsewhere, which in turn stimulate the related industrial sector.

The potential of fusion energy and recent advances in fusion research has drawn increasing interest from many private investors and entrepreneurs, because of the extent of the opportunities offered by this technological development and the increasing confidence in fusion technology for the long run. As a result, the number of privately funded companies that are participating in fusion-related projects has strongly increased in the past 30 years. The years to come will indeed be what Fusion Energy Base called 'exciting times', where the physics and mechanics will increasingly meet with the new information and communication technologies such as quantum computing and machine learning dealing with complex algorithms (Wurzel, 2020). Also, the availability of materials (such as high-temperature superconductors) is enabling small-scale experimentation that in turn helps to reduce the prohibitive costs of large projects (Wurzel, 2020), while contributing to the research effort on an international scale. Most privately funded companies focus on just one or two target technologies (e.g., high-temperature superconductors, liquid metal walls, magnetic target fusion), but they do not cover the full spectrum of challenges that need to be tackled, as the European Fusion Roadmap does. Instead, they leave the development of

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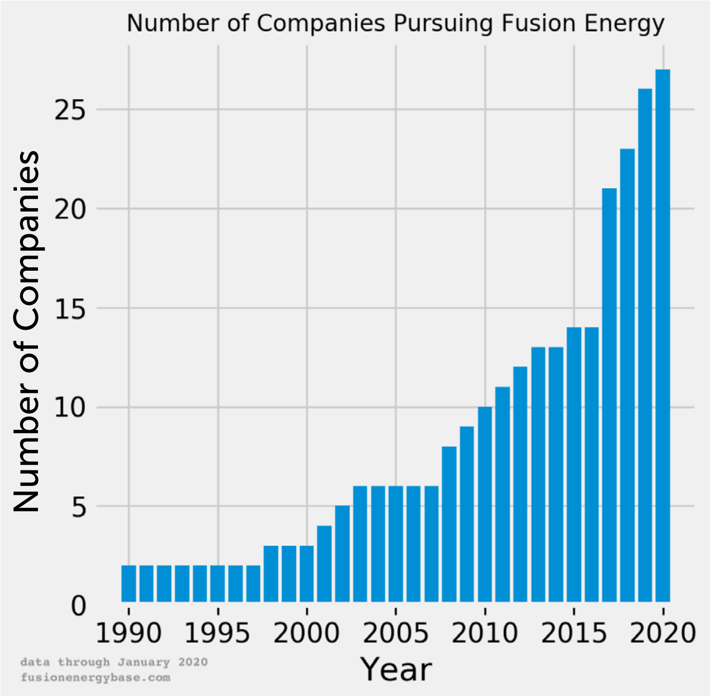
key technologies such as tritium breeding and reactor materials, as well as the regulatory environment and training of a skilled workforce, to public research programmes and projects such as ITER. What they are very good at is the rapid development of specific technologies and experimental machines to test them using a continuous build process. Their high-risk approach to fusion research may also lead to an unexpected breakthrough, which is what interests their venture-capitalist backers.

Figure 5: Growth of the number of for-profit companies pursuing commercially viable fusion energy in a given year.



Source: Wurzel, 2020.

A nuclear fusion race?

Considering the investment framework and looking at the global trend of energy companies shifting their interest from oil toward a broader energy investment, it is possible to make a comparison between fusion energy commercialisation and fossil fuels as the 'timeline for a typical upstream oil project from discovery to commercialization is on average about 10-15 years. This timeline is comparable to those proposed by many of the companies that are currently working towards commercialization of fusion energy' (Feygin, 2020).

However, it should be clear that it would be impossible for a single company to comprehensively solve all the challenges of replicating fusion energy on Earth. Each of these companies are focusing on individual issues while expecting some of the material technologies to be provided by other companies. This means that none of these companies are able to currently deploy technologies or generate fuel in commercial power plants, but rather are investigating and experimenting on one of the many technologies that might be implemented in bigger projects. This represents an 'R&D race', in which a successful technological development and experiments might be adopted in a commercial power plant.

As anticipated, most of the projects achieving technological steps toward fusion energy are shared among different institutions and investors. A good example of the multi-stakeholder cooperation to achieve this technology is Eni (which contributed to different fusion projects as an energy company), which in 2022 announced that, in collaboration with Massachusetts Institute of Technology labs, it had successfully completed a test of high-temperature superconductor magnets. The non-stop research approach that the different contributors are following is essential in solving technological challenges with the hope that they might be used by someone else in a future power plant. Despite being just one possible step towards the achievement of large-scale development, these innovative technologies are key to the successful energy transition, while 'magnetic confinement fusion (MCF) holds a pivotal role in the technological research for decarbonization'. Thus, MCF remains the most promising technology so far and 'a game changer' technology for our future (Eni, 2021).

Fusion in an international context

The most important publicly financed fusion energy research projects share their progress and advancements internationally. Many countries are or have been involved in experimenting with fusion power technologies over the past 50 years: Brazil, Canada, China, Costa Rica, Croatia, Czech Republic, Denmark, France, Germany, Italy, Japan, South Korea, the Netherlands, Portugal, Russia, Spain, Switzerland, the United Kingdom, and the United States.[8] Even during the Cold War, there was a constant and open exchange about fusion research between the East and the West. The ITER project was initiated during the Geneva Summit by US President Ronald Reagan and USSR's leader Mikhail Gorbachev back in 1985. Progress made by all countries is openly discussed every two years at the Fusion Energy Conference organised by the International Atomic Energy Agency.

In recent years, however, several countries have announced very aggressive programmes to develop nuclear fusion as an energy source. The White House recently launched its 'Bold Decadal Vision for Commercial Fusion Energy' (US Department of Energy, 2022), while a similar plan has been published by the UK Government (UK Atomic Energy Authority, 2021). China has initiated a very aggressive fusion programme and aims to get the Chinese Fusion Experimental Test Reactor, which is equivalent to the European DEMO reactor, up and running by 2040.[9]

With its Fusion Energy Roadmap, Europe has the most comprehensive and advanced plan to tackle all the remaining challenges, and it is presently the world leader in the field of fusion research: ITER is being built in France and Europe is responsible for 46 per cent of its construction; the world's largest tokamak JET is being used by EUROfusion; the world's largest stellarator is in Germany; and Spain is planning to build the IFMIF-DONES neutron source facility to test fusion materials under reactor conditions. Despite this leading role, the budget for fusion research in Europe is decreasing. Due to the COVID-19 pandemic, the decision was made in 2021 to divert funds away from fusion research and into the Covid Recovery Fund. This strongly hampers Europe's ability to maintain its decades-long, hard-won lead in this field and compete with very aggressive programmes that have been set up and are ramping up in a number of other

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[8] https://www.fusionenergybase.com/projects.

[9] https://en.wikipedia.org/wiki/China_Fusion_Engineering_Test_Reactor.

countries. The United States has recently stated that it wants to develop fusion in the coming decade in an effort similar to the Manhattan Project and the Moon Shot (Apollo). If nothing is done, and fusion budgets are not ramped up, Europe will lose its lead, with the risk that in the coming centuries it will need to buy technology from countries such as the United States and China.

When it comes to investment in technology, the EU took a step forward when it included nuclear energy (both fission and fusion) in the EU climate taxonomy. This means that energy produced in nuclear plants is intended as a non-polluting means to achieve climate neutrality, therefore suitable for private and public capital investment. Nevertheless, this decision has not yet led to an increase in public funding for nuclear fusion research.

The EU framework and the context of the Green Deal

When it comes to sustainability, it is not a secret that there is a CO2 cost to fusion – as there is for the construction of any kind of power plant or means of alternative energy generation. This carbon footprint does not come from the fusion process itself, but from the concrete and steel used to construct the power plant. Given new European strategies and the Green Deal aiming to soon produce these materials with a close-to-zero carbon footprint, the carbon footprint should fall significantly, perhaps even to zero, by the time Europe is ready to build its first generation of nuclear fusion power plants.

Moreover, in the context of the EU's decarbonisation, fusion technology is essential as it can complement intermittent energy sources such as solar PV and wind by providing the baseload electricity that we all count on. With no chance of a runaway reaction or meltdown, if fusion power plants are built to safely contain tritium, then they could be built close to the point of use. To give an example, DEMO, intended as a technology demonstrator and not a commercial plant, is 100–200 times as land-efficient as an equivalent solar power installation. A full commercial plant should double this. And while fusion power plant materials can all be reused after 100–300 years, solar PV panels, and wind turbine blades and footings are non-recyclable.

On the other hand, problems of strategic autonomy, especially when it comes to the technology supply chain, might be mitigated by enhancing internal market initiatives and fostering European champions. The supply and value chains for building fusion reactors should rely more on providers from the EU once the experimentation phase ends. Dedicated standards, and security and competition rules within the EU regulatory framework, will be crucial for the success of the commercial deployment of fusion technologies. Whether or not the EU will be a regulatory champion in this field will determine the success of a resilient 'regulatory power' that sets high standards without hampering technological development.

Connecting the dots: technology for (future) sustainability

Despite the high commitment of many countries and the efforts by European institutions to succeed in achieving MCF technology for energy production, the link to the EU's sustainable, green, and carbon-free transition is still to be properly defined. While the whole world would undoubtedly benefit from the success of the ITER experiment, the urgent need to take actions to tackle climate change has pushed EU institutions towards a very tight schedule, which might not match the needs of experiments with such a complex technology.

While the tokamak MCF approach studied by EUROfusion/ITER is the most advanced and promising way of achieving this technology, perhaps in a few decades scientists will discover that other approaches work better. The key is to first get this approach to work. By so doing, the interest and support will be created to advance the many other approaches to recreating the nuclear fusion on Earth. As with nuclear fission, nuclear fusion will advance through different generations of power plant technologies.

> What is clear is that there is enough fuel on Earth to meet our energy needs for thousands, hundreds of thousands, perhaps even millions of years if we can make fusion technology work. It is not only a matter of technology enthusiasm, it also means bringing the most advanced and promising approach to harnessing the fusion process as an energy source.

More broadly, linking the idea and the whole discussion around sustainability with that of advanced technologies is fundamental for many reasons. First of all, this allows policymakers to base their decisions on a strong scientific background, defining precise targets and reachable objectives based on quantifiable scientific knowledge. In turn, this would raise the level of the discussion around climate change, hand in hand with the growing interest (especially among the younger generations) about this issue. Finally, 'techno-sustainability' will lead to better strategic communication, avoiding alarmism or polarisation in the political discussion.

Conclusions and policy recommendations

First and foremost, despite the fact that MCF is still far from being implementable on a large-enough scale, the development of such technology will have astonishing implications for the future of energy: it stands to completely disrupt the energy market and mark the transition from fossil fuels being a source of power and money to a world in which access to fusion technology will be key. The necessary fuel (lithium and deuterium) can be found almost anywhere in the world in enough quantity for countries to be fuel-independent in a future where fusion power plants will be deployed. Despite the main technical limitations and challenges briefly exposed, the scientific community's achievements in the field are remarkable.

Furthermore, there is a paradigm shift in the whole concept of the operational scheme of a power plant. As briefly described, these complex power plants integrate hundreds of systems working together, creating technological complexity and difficulties in handling the materials, complex hardware, and software for remote operation. This creates a complex value chain that will require highly skilled personnel both for the design and operation of future fusion power plants. Geopolitically, there will be a shift away from fuel reserves being a source of power and money, to a world where access to this highly complex integrated system for fusion technology will be the key. First and foremost, EU institutions need to help encourage research projects and investment in high-skill generations of personnel as a priority.

If, on the one hand, a realistic commercial large-scale spread of fusion power cannot be expected before 2050, on the other hand, we are 'only' 28 years away from that achievement. According to the EUROfusion Roadmap, the first demonstration power plant would start operating in 2055. It would then take another 10–20 years for a commercial power plant to start; as such, large-scale diffusion would take a long time. This has led to the consideration that such technology must be considered not only a priority but a – real – opportunity to overcome the problems of energy supply and achieve a carbon-free economy in the future – as planned in the European Green Deal. While it is obvious that commercial fusion and energy-storing farms cannot realistically be deployed before 2050, what the EU can do is ensure a smart regulatory environment for fusion, one that is adaptive and capable of moving quickly. This would pave the way for the scientific community to come up with breakthroughs that could hasten the industrial deployment of fusion.

While it is not easy to give concrete policy recommendations, and because the main ongoing projects within this field are mainly shared internationally, the main scope of a pro-fusion (policy) agenda should be to ensure the long-term continuity of projects focusing on international cooperation. Europe could promote the EUROfusion programme, awarding it funds to advance more rapidly along its roadmap (and thereby bringing fusion electricity generation forward), while possibly also directing funds to a series of new European start-ups that would take high-risk approaches in the hopes of a breakthrough that would accelerate this progress even more. As the CEO of Commonwealth Fusion System asserted, the 'world needs a fundamentally new technology that will support efforts to decarbonise on a timeline that can mitigate climate change' (Commonwealth Fusion Systems, 2021).

Because of Europe's commitment to fighting climate change through a sustainable transition, it must be prepared to welcome such technologies among the other existing options for producing clean energy, simplifying and streamlining rather than raising regulatory barriers. This would facilitate these technological advancements so that Europe would be able to remain a strategic actor at the forefront of the future energy supply.

Another important element is the question of social acceptance of fusion-based technologies, central to which is better communicating the advantages of fusion energy and involving citizens in the development and adoption of this game-changing energy. This is necessary, especially given the interest among EU citizens, especially younger people, in addressing climate change and the environment. Informing citizens and involving them in the development of commercial energy might also draw the interest of new and future researchers, creating a new generation of highly trained and capable scientists with many different specialisations, contributing to fusion energy projects and helping to bring about a future fuelled by fusion. It would be particularly timely to have a discussion around fusion energy as a viable solution for our greener future. Finally, in pursuit of achieving European sovereignty, and given the commitment of the European Commission to making 'Europe the epicentre of "green tech"' (European Commission, 2020a), it is undoubtedly necessary to have discussions on the political level about technology that can enable the transition to a future where energy will flow as freely as water.

Some of the aspects highlighted in these few pages might seem either overly or insufficiently technical. Such technology is much more than just scientifically amazing both in terms of achievements for science and research. On the one hand, it allows us to discuss possible alternatives for energy supply. On the other hand, the international dimension of these initiatives allows the aims of cooperation to extend beyond national borders, in line with the founding principles of the Union. Sustainability and technology, or techno-sustainability, finally, must go hand in hand: only in this way will the objectives be achieved in a truly sustainable way, grounded in scientific evidence and shared internationally.

Despite geopolitical circumstances and strategic de-alignment between partners and rivals, the EU should foster research projects that can solve the abovementioned challenges together, in a global collaborative effort where the final result will be shared. Europe's expertise and experience can contribute to this global fusion race, while the EU's regulatory power might be of help to better allocate resources, representing best practice on how to balance research projects and commercial deployment of this technology. ■

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About ELF

The European Liberal Forum (ELF) is the official political foundation of the European Liberal Party, the ALDE Party. Together with 47 member organisations, we work all over Europe to bring new ideas into the political debate, to provide a platform for discussion, and to empower citizens to make their voices heard. Our work is guided by liberal ideals and a belief in the principle of freedom. We stand for a future-oriented Europe that offers opportunities for every citizen. ELF is engaged on all political levels, from the local to the European. We bring together a diverse network of national foundations, think tanks and other experts. In this role, our forum serves as a space for an open and informed exchange of views between a wide range of different EU stakeholders.

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