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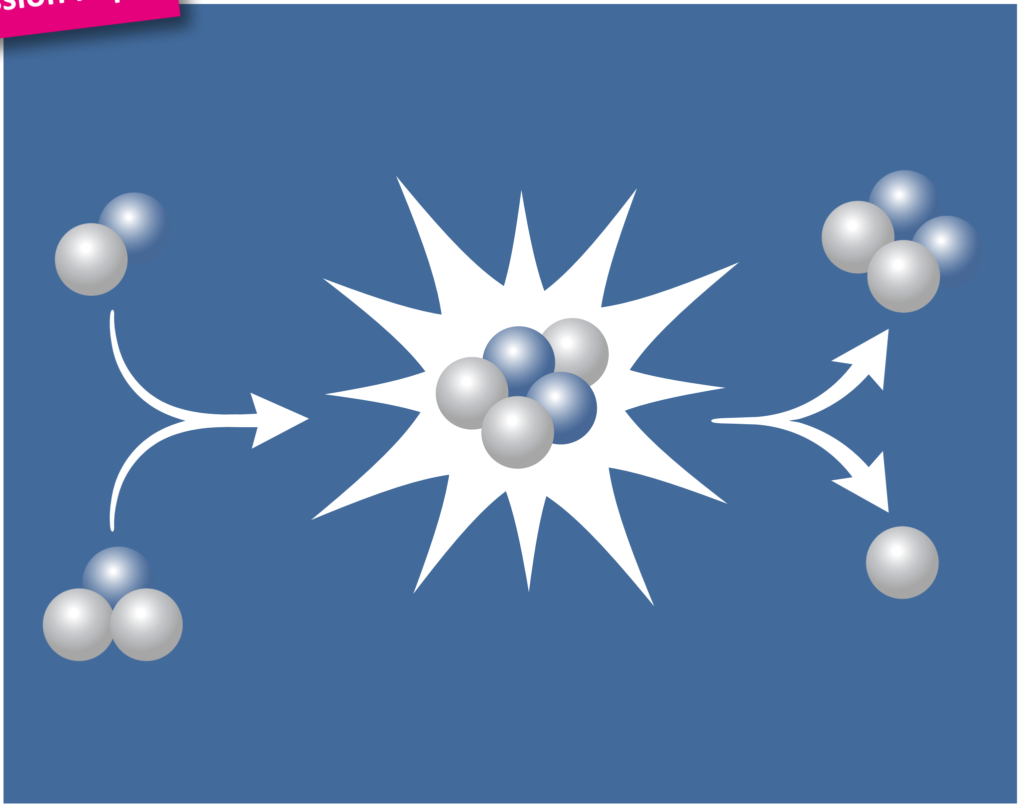
Discussion Paper

Can Nuclear Fusion Contribute to a Net-Zero Energy Supply?

Opportunities, Challenges and Timeframes

Sven Wurbs | Sonja Dehlwes | Andrea Lübke | Cyril Stephanos | Philipp Stöcker |
Manfred Fischedick | Hans-Martin Henning | Andreas Löschel | Ellen Matthies |
Karen Pittel | Jürgen Renn | Dirk Uwe Sauer | Indra Spiecker genannt Döhmann

Discussion Paper



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Fact sheet / November 2024

Can Nuclear Fusion Contribute to a Net-Zero Energy Supply?

What is nuclear fusion?

In nuclear fusion, **light atomic nuclei merge** to form new elements with a higher number of particles in their nucleus. For example, two hydrogen nuclei can fuse together to form a helium nucleus. Depending on which chemical elements are used, the fusion reaction releases energy.

The aim of fusion research is to harness this process that takes place continuously in the Sun in order to produce electricity here on Earth. But doing so poses major technological challenges, since **very high temperatures and in some cases high pressures are needed to achieve a nuclear fusion reaction**.

What's so interesting about nuclear fusion?

The goal of nuclear fusion research is a climate-friendly, **continuously available energy source** that requires less space and is powered by fuels that can be produced on site.

There have been high hopes that we are close to a breakthrough enabling a new, climate-friendly means of energy production ever since late 2022, when researchers at the National Ignition Facility in California achieved the first nuclear fusion reaction in the lab to produce more energy than the energy input into the plasma chamber to start the reaction.

We know the physics, but several practical challenges remain

The **physical processes** underlying nuclear fusion are understood. But solutions to various **practical challenges** must be found before a fully operational power plant can be built. These include:

- the supply of the **tritium fuel**
- a better **energy balance** – there is still a big discrepancy between the energy input and output
- **materials** capable of withstanding the high temperatures and neutron bombardment inside the reactor over long periods
- high-power **lasers** and efficient **high field magnetic coils**

First power plants unlikely before 2045

Nuclear fusion research is still **at the basic or in some cases applied research stage**. As yet, there is no definitive power plant design for either of the two fusion concepts (magnetic confinement fusion and inertial confinement fusion).

Given the amount of development work that still needs to be done, the **first fusion power plant is unlikely to be built until 2045 at the earliest**, and there is no guarantee of successful implementation at all. To make it happen, all the unresolved research and development questions will need to be addressed intensively and in parallel.

Keep researching nuclear fusion, but not at the expense of the energy transition

If successfully implemented, nuclear fusion could contribute to a climate-friendly energy supply in the longer term. However, it is unlikely to help Germany and Europe meet their **2045/50 climate targets**.

While there is good reason to continue researching nuclear fusion, this should not be at the expense of efforts to develop and build a climate-friendly energy system centred on renewable energy.

Abbreviations and acronyms

Ba	barium
CO_2	carbon dioxide
Cs	caesium
D/^{2}H	deuterium
D_2O	heavy water (deuterium oxide)
DAC	direct air capture
DD	direct drive
DEMO	DEMOnstration Power Plant
EAST	Experimental Advanced Superconducting Tokamak
ESYS	Academies' Project "Energy Systems of the Future"
EU	European Union
Fe	iron
FI	fast ignition
H	hydrogen
He	helium
IAEA	International Atomic Energy Agency
ICF	inertial confinement fusion
IDD	indirect drive
IPP	Max Planck Institute for Plasma Physics
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
KIT	Karlsruhe Institute of Technology
LCOE	levelised cost of electricity
LHD	Large Helical Device
LLNL	Lawrence Livermore National Laboratory
LMJ	Laser Mégajoule
MCF	magnetic confinement fusion
MeV	megaelectron volt
MIT	Massachusetts Institute of Technology
N	neutron
NIF	National Ignition Facility
p+B	proton-boron reaction
Pu	plutonium
SI	shock ignition
Sr	strontium
T/^{3}H	tritium
TRL	technology readiness level
U	uranium
USA	United States of America
WHO	World Health Organization

Glossary

Base load power plants	Base load power plants are power plants that are technically capable of continuous operation. The electricity they generate covers the part of the electrical load (capacity) that is required at all times in their supply area. Intermediate load and peak load refer to additional capacity that is not required at all times. [7, s.v. Grundlast]
Beta emitter	Beta emitters are substances that emit beta particles – electrons (e-) or their antiparticles positrons (e+) – during radioactive decay. Beta radiation is thus particle radiation comprising electrons emitted during the radioactive decay of atomic nuclei. [1, s.v. Betastrahler, Betastrahlung]
Binding energy	The energy required to disassemble a nucleus into the individual nucleons it is composed of. Binding energy is the energy equivalent of the mass defect, i.e. the difference between the actual atomic mass and the sum of the individual masses of the protons and neutrons in the atomic nucleus. [4, s.v. Bindungsenergie]
Blanket	The blanket is the layer of the reactor just beyond the first wall. It decelerates the fast fusion neutrons emitted during the nuclear fusion reaction. In the blanket, the kinetic energy of the fusion neutrons is converted into heat which is removed from the reactor core by a coolant and used to produce electricity. It is also envisaged that tritium fuel for the fusion reaction will be produced from the interaction of the decelerated neutrons with lithium in the blanket. In magnetic confinement fusion, a thick layer on the rear wall of the blanket shields the magnet coils and outer parts of the reactor from the neutrons. [2, s.v. Blanket]
Bremsstrahlung loss	Shortwave electromagnetic radiation produced by the deceleration of electrons in matter due to the Coulomb interaction between the electrons and the atomic nuclei. [4, s.v. Bremsstrahlung]
Confinement time	Also known as energy confinement time. In fusion research, this is the time it takes for the plasma to lose its energy content through internal transport processes (diffusion), heat conduction and radiation. [4, s.v. Energieeinschlusszeit]
Cost degression	Cost degression occurs when a product's unit cost falls for every additional unit produced. This is mostly the case for products with high fixed costs. [3]
Coulomb barrier	The potential barrier around a nucleus. A positively charged particle must cross this barrier to enter or leave the nucleus. As well as the particle's charge, the effective height of the Coulomb barrier is determined by its kinetic energy and its angular momentum. [4, s.v. Coulomb-Barriere]
Cryostat	A thermally insulating vacuum vessel enclosing a superconducting tokamak or stellarator. With its help, the reactor's superconducting magnets are kept at low temperature. [2, s.v. Kryostat]
Decay time	The time it takes for a steadily decreasing physical variable such as radioactivity to fall to a given fraction of its initial value. [4, s.v. Abklingzeit]
Defence-in-depth	The Safety Requirements for Nuclear Power Plants, Section 2 (1), stipulate that "A defence-in-depth concept shall be realised that ensures the fulfilment of the fundamental safety functions and the preservation of the barriers and retention functions on several consecutive levels of defence as well as in the case of any internal and external hazards." [5]
Derivative	A chemical compound produced by removing, adding or exchanging atoms or groups of atoms of a parent compound. The derivative's structure or properties remain similar to those of the parent compound. [4, s.v. Derivat]
Deuterium	Deuterium (D) or "heavy hydrogen" is a naturally occurring isotope of hydrogen. Its atomic nucleus comprises one proton and one neutron. [2, s.v. Deuterium]
Direct Air Capture	A carbon removal technology that captures carbon dioxide (CO_2) from the air using chemical sorbents. The CO_2 can then be used as a feedstock (Carbon Capture and Utilisation – CCU) or compressed and stored underground (Carbon Capture and Storage – CCS).
Direct drive	In fusion research, an inertial confinement fusion method that compresses the fuel by firing laser or ion beams directly at it.

Divertor	Part of the reactor core situated at the bottom of the plasma vessel. It diverts impurities that come off the inside of the reactor wall and the waste products of the nuclear fusion reaction (especially helium) away from the plasma vessel interior. The divertor regularly comes into direct contact with the outer edge of the plasma. [2, s.v. Divertor]
Energy balance	A comparison of the energy of a system's components before and after a process such as a chemical or nuclear fusion reaction. [4, s.v. Energiebilanz]
Energy sovereignty	Strategic sovereignty in the realm of energy is characterised by an environment in which sufficient, reliable and affordable energy supplies and services are provided in a manner that does not conflict with, or further yet, endanger a country's values, interests or foreign policy goals. [6]
Fast ignition	A form of inertial confinement fusion where the compression and ignition phases induced by laser or energy pulses are decoupled. The nuclear fusion reaction is initiated by a separate pulse that is delivered directly inside the pre-compressed target through a hole or "cone". [17]
Final disposal	The safe disposal or storage of (high-level) radioactive waste in accordance with the provisions of the German Atomic Energy Act. As well as the waste's activity, the half-lives of its contents are also a key factor in its classification (from low-level to high-level) and disposal. Before being permanently stored in a sealed final repository, high-level radioactive waste is temporarily stored for a few decades at the power plant site or external interim storage facilities until the radiation from the shorter-lived isotopes has decayed. [1, s.v. Endlagerung] and [4, s.v. Endlagerung]
Flexibility (energy supply)	In order to maintain a balance between the amount of energy fed into and drawn from the power grid, technologies are needed to compensate for the intermittent nature of wind and solar power. These include power storage systems, flexible power plants with rapidly adjustable outputs, and consumers able to at least partly defer their electricity consumption to times when a lot of wind and solar power is being fed into the grid.
Fossil fuels	Energy carriers with a finite supply, created from biomass at high pressures and temperatures over millions of years. These energy resources – oil, coal and gas – are formed of different carbon compounds. [14, s.v. erneuerbare Energien]
Fuel	Reactants/materials used to produce energy. In nuclear engineering, heat is produced by atomic reactions involving the merging of light nuclei (fusion) or the splitting of heavy nuclei (fission). [7, s.v. Brennstoff]
Greenhouse gas neutrality (net-zero greenhouse gas emissions)	The 2021 Federal Climate Change Act defines net-zero greenhouse gas emissions ("greenhouse gas neutrality") as an equilibrium between the anthropogenic emissions of greenhouse gases from sources and the reduction in the volume of such gases by means of sinks.
Heavy water	Water containing deuterium (D) instead of the more usual hydrogen (H). Its chemical formula is D_2O, where O denotes oxygen. [4, s.v. schweres Wasser]
Hydrogen bomb	A weapon powered by an uncontrolled thermonuclear reaction usually achieved by fusing deuterium and tritium and lithium to create helium. [4, s.v. Wasserstoffbombe]
Indirect drive	In fusion research, an inertial confinement fusion method where the fuel pellet is situated inside a cylindrical shell called a "hohlraum". The ion or laser beams are fired inside the shell, where they hit the hohlraum's inner wall, generating X-rays. The X-rays are directed at the surface of the fuel pellet, compressing it and igniting the plasma. [17]
Inertial confinement fusion	A nuclear fusion technology in which the compression and ignition of a small volume is induced by bombardment with laser or ion beams (inertial confinement). [4, s.v. Trägheitsfusion]
International Atomic Energy Agency (IAEA)	An intergovernmental organisation founded in 1957 to promote the peaceful uses of nuclear energy. Its headquarters are in Vienna. The IAEA is an autonomous organisation within the United Nations (UN). [1, s.v. Internationale Atomenergie-Organisation (IAEA)]
Isotopes	Atoms of the same chemical element that have the same number of electrons and the same number of protons in their nucleus, but a different number of neutrons (they thus have the same atomic number but a different mass number). Isotopes have the same chemical properties but different nuclear physical properties. [1, s.v. Isotop]

Kinetic energy	Kinetic energy is the energy that a body possesses by virtue of being in motion. It is equal to the work needed to bring the body to its current state of motion from a state of rest. [7, s.v. Bewegungsenergie]
Large power plant	A power plant with an especially high capacity – usually at least several hundred megawatts (MW) or even several gigawatts (GW) – that supplies electricity to as many as several million people. Smaller power plants mostly have a capacity of under 100 MW. [7, s.v. Großkraftwerk]
Laser fusion	An approach to nuclear fusion that aims to achieve […] fusion by firing focused laser beams from all sides at small (radius = 1 mm) fuel pellets. [4, s.v. Laserfusion]
Lawson criterion	The criterion describing the conditions required to ignite nuclear fusion in a fusion reactor. [4, s.v. Lawson-Kriterium]
Levelised cost of electricity	The levelised cost of electricity is the cost of supplying a unit of electricity (kilowatt hour or megawatt hour).
Life cycle assessment	A systematic evaluation of a product's environmental impact over the entire period of its life. This includes all the environmental impacts resulting from its production, use and disposal, as well as the associated upstream and downstream processes (e.g. production of raw materials and manufacturing supplies). [8]
Magnetic confinement fusion	An approach to nuclear fusion that aims to generate fusion power by using magnetic fields to confine the burning plasma. [9]
Magnetic field	The field that describes magnetic influence. It assigns a three-dimensional vector to every point in space and time. [4, s.v. Magnetfeld]
Net-zero technology	A technology that does not contribute to global warming. This means that it does not produce net emissions of carbon dioxide (CO_2) or other greenhouse gases like methane and nitrous oxide. It use should not have any negative climate impacts. [7, s.v. klimaneutral]
Neutron fluence	The neutrons impinging on one square metre of the plasma vessel wall throughout the lifetime of a fusion power plant. [2, s.v. Neutronenfluenz]
Neutron radiation	**th**Neutron radiation consists of neutrons – electrically neutral elementary particles. It is highly penetrating and extra shielding is thus required to protect against it. [1, s.v. Neutronenstrahlung]
Nuclear fission	Heavy atomic nuclei are split by bombarding them with neutrons, releasing large amounts of energy. Nuclear fission produces two medium-sized nuclei. As well as these radioactive fission products, it produces additional neutrons that can trigger further fission reactions. Nuclear fission can also occur spontaneously, without being externally induced. [1, s.v. Kernspaltung]
Nuclear fusion	A process that merges light atomic nuclei to form heavier ones. [2, s.v. Kernfusion]
Nucleon	A term that refers to protons and neutrons, the building blocks of atomic nuclei. [4, s.v. Nukleon]
Plasma	Plasma is also referred to as the "fourth state of matter". A plasma is composed of mostly ionised atoms or molecules and their free electrons. [2, s.v. Plasma]
Plasma chamber	Chamber where the nuclear fusion reaction takes place. This is where the fuels in the plasma combine to form a new element.
Proliferation	The spread of nuclear weapons (and sometimes also of biological and chemical weapons) as well as of knowledge about the technology needed to produce them. [10, s.v. Proliferation]
Pulsed operation	A non-continuous mode of operation where the device must be switched off and on again periodically. It thus comprises successive time blocks. Pulsed lasers emit light in bursts (pulses) of limited duration. [2, s.v. tokamak; 11]

Radioactive	In science, "radioactive" refers to the property whereby certain atoms transform into other atoms without external influence, emitting ionising radiation in the process. Radioactive atoms are called radionuclides. Germany‘s Atomic Energy Act defines a material as "radioactive" if it has a certain activity (contains a certain amount of radionuclides). [12]
Radioactive waste	If, according to the definition of Germany’s Atomic Energy Act, no further use is foreseen for radioactive substances, they are classified as radioactive waste. Radioactive waste arises from the use of ionising radiation in nuclear power plants, research, industry and, in small quantities, the healthcare sector. [13]
- **Low-level**	Radioactive waste that does not require additional shielding for its containers during handling. [1, s.v. schwachradioaktive Abfälle]
- **Intermediate-level**	Radioactive waste that requires additional shielding for its containers during handling. [1, s.v. mittelradioaktive Abfälle]
- **High-level**	High-level radioactive waste is characterised by high activity concentrations and thus high decay heat. [1, s.v. hochradioaktive Abfälle]
Reactor	A device for producing heat from nuclear energy. [4, s.v. Reaktor]
Renewable energy	Energy sources that are constantly replenished on a human timescale. [14, s.v. erneuerbare Energien]
Repulsive force	A force that tries to increase the distance between particles or particle systems. It is caused by a strong interaction (nuclear force) between like electrical charges or magnetic poles, for example. It is also known as negative attraction. [4, s.v. Anziehung]
Stellarator	A type of magnetic confinement fusion reactor design: in a stellarator, the helical spiralling of the magnetic fields is achieved solely by means of the shape of a set of external coils. Unlike tokamaks, the design of stellarators allows them to operate in continuous mode. [2, s.v. Stellarator]
Superconductor	Certain materials can conduct electricity with no resistance if cooled to a particular – usually very low – temperature. These materials are called superconductors. [2, s.v. Supraleitung]
Target	Material that accelerator beams are fired at – usually shaped as a pellet or capsule – and that contains fuel. [4, s.v. Target]
Technology readiness level	The technology readiness level scale goes from 1 to 9. It is used to estimate which of the defined development phases a technology is currently in. The aim is to achieve a successful, usually commercial, application.
Tokamak	A type of magnetic confinement fusion reactor design: in a tokamak, the plasma is confined by two superposed magnetic fields: firstly by a toroidal field produced by external coils and secondly by the field of a ring current flowing in the plasma. The field lines in the combined field are helical. The tokamak also requires a third, vertical field that fixes the position of the current in the plasma vessel and shapes the plasma edge. [2, s.v. Tokamak]
Triple product	The combination of temperature, particle density and confinement time. The triple product is a measure of how close the plasma comes to meeting the conditions for self-sustaining nuclear fusion. [26]
Tritium	Tritium (T) or “super-heavy hydrogen” is an isotope of hydrogen. Its atomic nucleus consists of a proton and two neutrons. [2, s.v. Tritium]
Tritium breeding	The process of producing the tritium fuel inside the plasma chamber itself. Lithium interacts with the neutrons emitted from the fusion process to produce tritium. [2, s.v. Tritium]

Summary

The current state of nuclear fusion research

There are high hopes that nuclear fusion can help to deliver a secure and climate-friendly energy supply. As well as the need to end the use of fossil fuels, these hopes are driven by the research successes achieved in recent years at, among others, the NIF (USA), JET (United Kingdom), EAST (China) and Wendelstein 7-X (Germany) test facilities. Nonetheless, most nuclear fusion research is still at the basic research stage, although some components such as lasers, superconducting magnets and plasma heating systems are now progressing to the applied research stage.

There is still a long way to go before a fully operational nuclear fusion power plant can be built. None of the different fusion concepts has a prototype power plant yet. And it is not just the technological feasibility of a commercial-scale fusion power plant that has yet to be demonstrated – the commercial viability of any such plant must also be proven. In other words, a number of major challenges will need to be overcome if the vision of a nuclear fusion power plant is to become reality. Many experts estimate that the first prototype or commercial power plant will only be realised in 20 to 25 years' time. If this is to happen, nuclear fusion research funding will need to be maintained, the necessary developments will need to be driven in parallel, and all the stakeholders will need to cooperate closely with one another. Shorter timeframes of 10 to 15 years are being talked about in some quarters, especially the startup community. However, given the current state of research, it seems unlikely that the first power plant can be built within such a short period. Consequently, nuclear fusion will be unable to contribute to meeting the statutory climate targets and achieving net-zero greenhouse gas emissions by 2045 in Germany and 2050 in Europe. At best, any contribution it does make will come towards the end of this period and will be correspondingly small. That said, fusion power plants could help to meet the expected increase in global electricity demand in the second half of the century.

Opportunities and challenges

Successful implementation of nuclear fusion would bring various benefits. Fusion power plants would provide an additional low-emission power generation technology to supplement renewable energy. Unlike fossil fuel power plants and nuclear fission, fuel could be produced on site and would be available on a long-term basis, reducing reliance on exporting countries. The potential risks of nuclear fusion are lower than for nuclear fission, not least because there is no danger of an uncontrollable chain reaction. Other general benefits often cited by the experts include the fact that fusion power plants require less space and the opportunity to export complex, high-tech fusion systems or individual power plant components. The use of high-tech components developed for nuclear fusion in other areas such as medicine, optics, diagnostics, robotics and space travel could provide further economic opportunities and help to reduce investment risks.

These benefits must be weighed up against the high investment required for the initial development of the technology and the eventual construction of fusion power plants, which will in all likelihood involve large-scale projects. Furthermore, the power plants will need to show that they can be commercially competitive in the energy supply landscape of the mid-21st century. As far as the timescale for resolving the remaining technological challenges is concerned, it is important to bear in mind that the development of fusion power plants could take longer than expected or, in the worst-case scenario, that it may not be possible to achieve sustained operation at all. Like fission power plants, most fusion power plants would also generate radioactive waste. However, it would not be high-level waste, which would not have to be stored for longer than around 100 years.

Overall, there is good reason to press ahead with nuclear fusion projects. However, this should not be at the expense of efforts and measures to meet the 2045/2050 targets for a net-zero energy system. On the contrary, the two strategies should complement each other so that they can jointly contribute to the long-term security and sovereignty of German and European industry.

Nuclear fusion's role in a net-zero energy system

If commercial nuclear fusion can be successfully realised, its low CO_2 emissions mean that it could form part of a climate-friendly electricity system from the second half of the century. Nuclear fusion's ability to compete with renewable energy and other low-emission technologies in the electricity market depends on the cost at which fusion power plants are able to supply electricity. System studies have looked at the whole-system costs including power storage systems, grids and other infrastructure rather than just the plant-based levelised cost of electricity. They conclude that nuclear fusion will only contribute to lower system costs if its levelised cost of electricity is at the lower end of the currently projected range. It is important to stress that there is presently a lot of uncertainty about these projections due to the fact that the technology is still in the early stages of development and several challenges have yet to be overcome. When considering this conclusion, the cost trends for other net-zero energy technologies must also be borne in mind, since these will have a significant influence on nuclear fusion's potential commercial applications.

It is likely that any fusion power plants built around 2050 in Germany and Europe will encounter a profoundly transformed energy system based on renewable energy and with a more decentralised structure. Fusion power plants could be integrated with the system as long as it is flexible enough. This flexibility could be enabled by electricity and energy storage systems, targeted demand (load) management and greater use of digital technology, for example. Based on current knowledge, however, system studies do not consider fusion power plants to be necessary for a secure and reliable future energy supply. From today's perspective, the influence that the availability of fusion power plants could have on the energy system's development post-2050 is difficult to predict. The high investment requirements mean that they would probably operate in a similar way to today's base load power plants, mainly being used in situations where there is a constant demand for energy. This high level of demand could occur in densely populated areas or industrial centres. It could also arise from the production of hydrogen and potentially also its derivatives in Germany and other European countries. Nuclear power plants in particular could be gradually replaced by fusion power plants especially in countries whose energy systems still rely on large power plants.

The key role of funding and regulation in enabling fusion power plants

Nuclear fusion is a complex, research-intensive technology that can only be realised if the extensive funding it has already received is supplemented by substantial additional public and private research funding. The growing number of startups pursuing the commercial implementation of nuclear fusion are helping to attract this funding. As well as raising additional research and development funding from private investors, these startups are also expanding the range of technological solutions that could potentially be deployed.

The realisation of fusion power plants will also require a stable regulatory framework. This includes assigning responsibilities to the relevant regulatory and supervisory authorities and setting standards for the licensing and operation of nuclear fusion power plants. It will also be necessary to address the operational safety, occupational health and safety and environmental aspects of working with toxic and radioactive materials, for example. There are strong calls from the fusion community for fusion to have its own specific regulations. They also argue that fusion's regulatory framework should not be closely based on the regulations for nuclear power plants, as the potential risks of fusion are lower than for nuclear fission. Since nuclear fusion does not yet have its own regulatory framework and the technology is still at the development stage, an iterative approach should be taken to the regulatory framework's development so that new findings can be incorporated and any necessary amendments made.

Introduction

The transformation of the energy system required to achieve a net-zero energy supply by the second half of the century poses major challenges for the energy industry. It will call for the use of non-fossil energy sources and new methods of producing electricity, heat and energy carriers like fuels. In addition to the different types of renewable energy (primarily solar PV, onshore and offshore wind, hydropower and geothermal energy), nuclear fusion is increasingly being mentioned in the public debate as a technology that could contribute to the future energy supply.

Researchers have spent decades trying to develop technologies that would enable the processes that constantly fuse atomic nuclei in the Sun to be replicated here on Earth. The goal is to harness the energy generated from nuclear fusion processes as an energy source for the human population. The fundamental physical processes underlying nuclear fusion are largely understood. However, the technological implementation has proven challenging, and there are still no commercial fusion power plants or even prototypes in the world today.

Despite the fact that the technology is still in its infancy and requires extensive further research, there are very high hopes in some quarters that nuclear fusion could meet a significant part of our energy needs in years to come. These hopes are fuelled by the research successes that have been reported in the media over the past few decades, with varying degrees of publicity. But what is the current state of nuclear fusion research? What opportunities would it offer for businesses and the energy supply if it could be successfully implemented? And which challenges must still be overcome before this is possible? This discussion paper addresses these and several other questions. It also looks at the possible timeframe for realising a fusion power plant based on current knowledge, how commercial fusion power plants would fit into the future energy system, and the safety requirements that would need to be in place if such plants were to be built.

This paper focuses on nuclear fusion's civilian, energy-related uses. It discusses the research and development activities of research institutions and startups aiming to realise fusion power plants that can supply electricity and potentially also waste heat. The starting point for this publication was a workshop run by the Academies' Project "Energy Systems of the Future" (ESYS), attended by leading experts from university and non-university research institutions and startups.[1] As well as the workshop's outputs, this paper is based on studies and scientific papers in the fields of nuclear fusion and energy system research, supplemented by expert opinion.

Some members of the research community prefer to use the terms 'fusion' or 'fusion energy' instead of 'nuclear fusion'. Among other things, this is to help distinguish it from nuclear fission, the established technology used in today's nuclear power plants. In this paper, however, 'nuclear fusion' is used in instances where the term occurs on its own. This is because the technology is based on physical interactions in atomic

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[1] The workshop took place on 13 April 2023 in Berlin. It was attended by Stephanie Dachsberger (acatech Office), Prof. Dr. Tony Donné (EUROfusion), Prof. Dr.-Ing. Manfred Fischedick (ESYS Board of Directors | Wuppertal Institute), Prof. Dr. Dr. h.c. Siegfried H. Glenzer (SLAC - National Accelerator Laboratory (Stanford University)), Dr. Ulrich Glotzbach (acatech Office), Prof. Dr. Sibylle Günter (Max Planck IPP/ EUROfusion), Prof. Dr. Constantin Häfner (Chair for Laser Technology, RWTH Aachen University | Fraunhofer Institute for Laser Technology | Fraunhofer Society), Prof. Dr. Hans-Martin Henning (ESYS Board of Directors | Fraunhofer ISE), Dr. David Kingham (Tokamak Energy), Dr. Heinz-Ullrich Kraft (FILO), Dr. Frank Laukien (Bruker Corporation | Gauss Fusion Initiative), Dr. Andrea Lübcke (acatech), Daniela Niethammer (ESYS Project Office), Prof. Dr. Karen Pittel (ESYS Board of Directors | ifo Institute), Prof. Dr. Hermann Requardt (Gauss Fusion Initiative | acatech), Prof. Dr. Markus Roth (Focused Energy | TU Darmstadt), Milena Roveda (Gauss Fusion Initiative), Prof. Dr. Dirk Uwe Sauer (ESYS Board of Directors | RWTH Aachen University), Dr. Cyril Stephanos (ESYS Project Office), Prof. Dr. Jan Wörner (acatech) and Sven Wurbs (ESYS Project Office). This paper does not reflect the views of individual workshop participants. It was written after the workshop by the named authors, who took the workshop's findings into account alongside various other inputs.

nuclei and because ‘nuclear fusion’ is widely used in the general public debate. In the interests of legibility, however, the abbreviated form ‘fusion’ is normally used in compounds.

1 Basic principles

1.1 How does nuclear fusion work?

In nuclear fusion, the light atomic nuclei of elements such as hydrogen merge to form new elements with a higher number of particles in their nucleus (nucleons)[2] (see Figure 1). Nuclear fusion releases energy because the mass of the resulting nucleus is lower than the sum of the masses of the original atomic nuclei (this is known as the “mass defect”). The kinetic energy of the particles is converted into heat through interactions with other particles or through radiation losses. This process takes place continuously in the Sun, but does not occur naturally on Earth. Thus, the aim of fusion research is to develop a technology to harness this process on Earth.

A lot of energy is needed to start a nuclear fusion reaction, since the atomic nuclei must be forced very close together. In order for the positively charged nuclei to merge, they must overcome the repulsive forces between them (known as the Coulomb barrier). This can happen when the nuclei come together at very high speeds, for example in environments with extremely high temperatures (several million degrees Celsius), when the particles form a plasma.[3] If the repulsive forces are overcome, the nuclei combine to form a new element. [15; 16; 17]

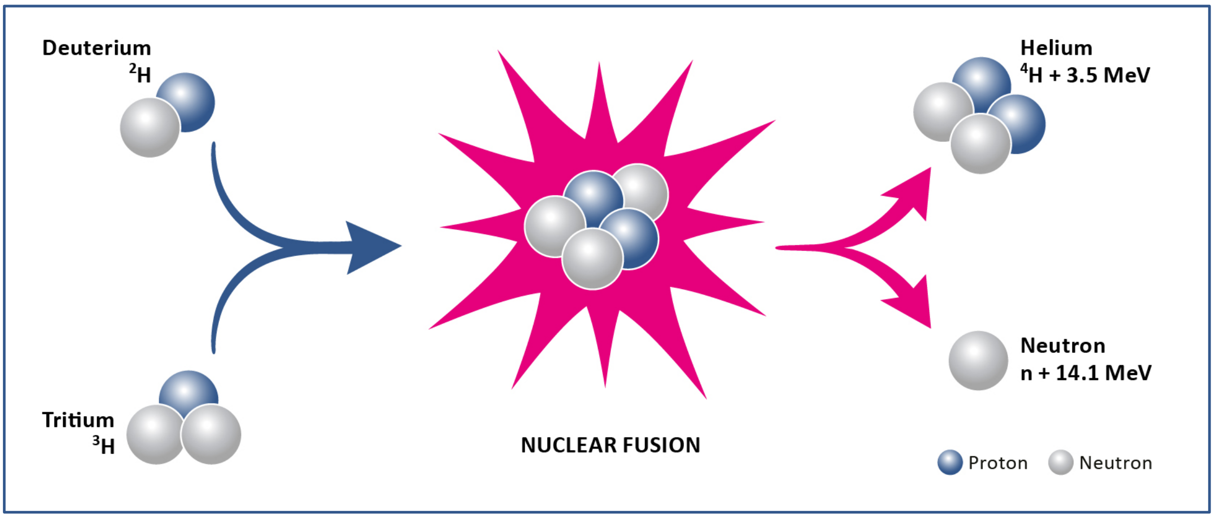

Figure 1: Principle of nuclear fusion as illustrated by the formation of helium (^{4}He) from the hydrogen isotopes deuterium (^{2}H) and tritium (^{3}H). A neutron (n) with a kinetic energy of 14.1 MeV (megaelectron volts) is released. The alpha particle (helium) with a kinetic energy of 3.5 MeV heats the plasma further, accelerating the fusion processes. Source: authors’ own illustration.

Nuclear fusion on Earth requires higher temperatures than those occurring in the Sun. The reason for this is the high pressure in the Sun’s core – since particle density increases with pressure, nuclear fusion can occur at lower temperatures in the Sun. This is reflected in the Lawson criterion, which describes the

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[2] Nucleons are the protons (positively charged particles) and neutrons (particles with no charge) that make up an atom’s nucleus. The mass number (written as a superscript to the left of the element’s symbol) denotes the total number of nucleons in an atomic nucleus.

[3] The plasma state is often described as the fourth state of matter, alongside the solid, liquid and gaseous states. Plasma is characterised by ionised atoms and free electrons.

conditions required for a self-sustaining nuclear fusion reaction in terms of the relationship between the plasma temperature, the particle density in the plasma and the plasma confinement time.[4] [18; 19; 20; 21].

1.2 The difference between nuclear fusion and nuclear fission

Even though both involve the release of binding energy from atomic nuclei, there is one key difference between nuclear fusion and nuclear fission.

In nuclear fusion, energy is released when light atomic nuclei – i.e. nuclei with a low number of nucleons – merge with each other (see Figure 2). Fusion produces elements with a higher number of nucleons and thus a higher binding energy in the nucleus.

In nuclear fission, on the other hand, energy is released by splitting heavy atomic nuclei with a high number of nucleons. Fission produces elements with a lower number of nucleons in the atomic nucleus.

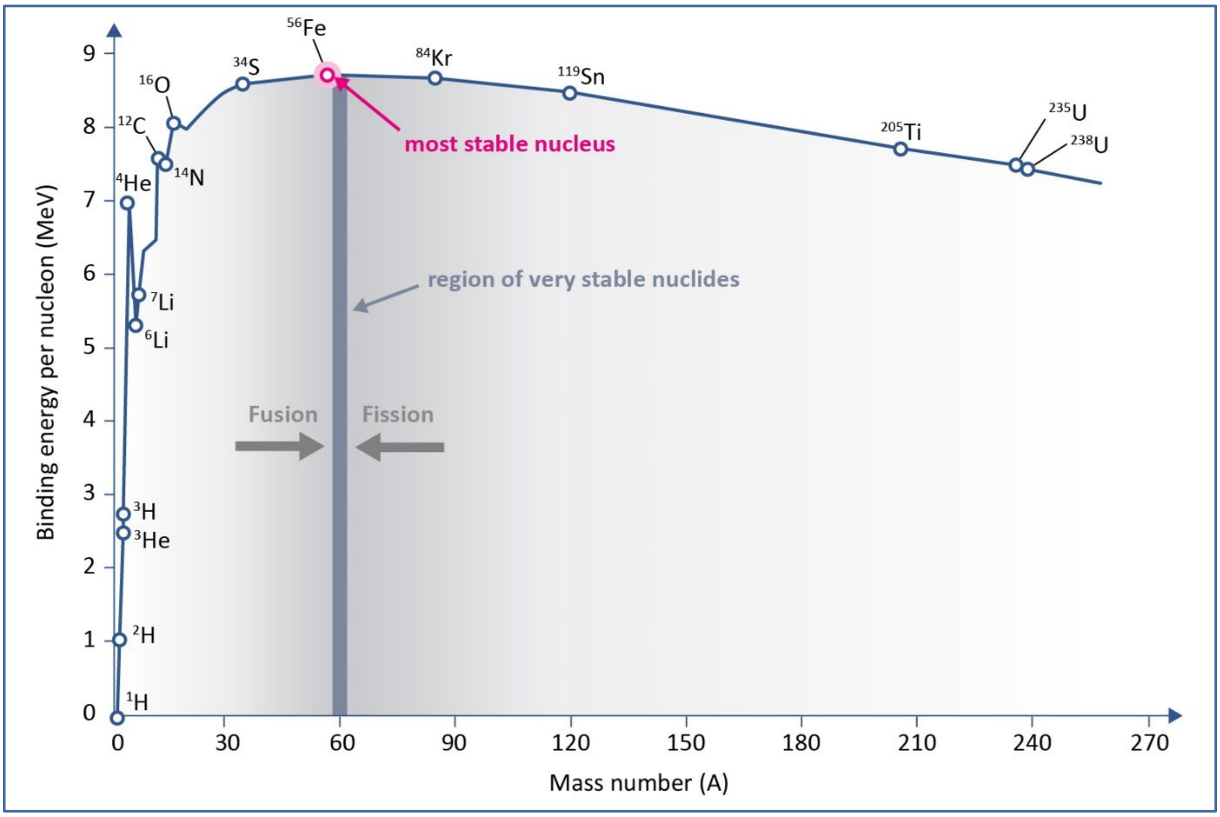

Figure 2: The occurrence of nuclear fusion or nuclear fission depends on the number of particles in the nucleus (mass number). Nuclear fusion occurs with elements with a low number of nucleons[5], whereas nuclear fission occurs with elements with a high number of nucleons. Iron-56 (^{56}Fe) has the nucleus with the highest binding energy, making it the most stable element. Source: adapted from LibreTexts, CC BY 4.0 Deed [22].

In nuclear fission, active measures must generally be taken to prevent a chain reaction from occurring, whereas there is no uncontrollable chain reaction in nuclear fusion. If the pressures or temperatures are lower than necessary, the nuclear fusion reaction quickly stops of its own accord. Another difference relates

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[4] The confinement time is the time it takes for the plasma's energy to dissipate into its surroundings. In inertial confinement fusion, an energy confinement time of 10^{-9} seconds is required for a plasma density of approximately 10^{25} cm^{-3}. In magnetic confinement fusion, the confinement time for a plasma density of 10^{14} cm^{-3} is 1 second. [18]

[5] The mass number (written as a superscript to the left of the element's symbol) denotes the total number of nucleons (protons and neutrons) in an atomic nucleus.

to the nature of the radioactive waste produced by nuclear fusion reactions – unlike nuclear fission, fusion does not usually give rise to high-level radioactive waste. In prospective fusion power plants, the danger posed by residual heat and decay heat is limited because the fuel is fed into the plasma chamber continuously or produced by the reactor itself. In contrast to nuclear fission power plants, the nuclear fusion reaction ends quickly. This means that unless more fuel is supplied, no more radioactive nuclei can be produced. It is these radioactive nuclei that emit decay heat and thus require systematic cooling.

INFO: The differences between nuclear fusion and nuclear fission

	Fusion	Fission
Process	• merging of atomic nuclei	• splitting of atomic nuclei
Fuels	• light elements and their isotopes, mainly the hydrogen isotopes deuterium (^{2}H) and tritium* (^{3}H)	• heavy elements, often uranium* (^{235}U) or plutonium* (^{239}Pu)
Reaction products	• depends on fuel • Example: deuterium and tritium: helium (^{4}He) + neutron	• depends on fuel • Example: uranium* (^{235}U): various radioactive materials (e.g. strontium* (^{90}Sr), caesium* (^{137}Cs), barium* (^{145}Ba)), neutrons, electrons and stable elements)
Temperature/energy production	• initially, extremely high, externally generated temperatures needed to start the reaction (approximately 100 million degrees Celsius) • nuclear fusion generates kinetic energy/heat that is used to produce energy	• approximately 290 - 1,000 degrees Celsius in the primary circuit[6] [23; 24] • fission process generates kinetic energy/heat that is used to produce energy
Safety	• no uncontrollable chain reaction, but can produce tritium* • radioactive waste is generated, depending on the fusion method used and the reactor materials and/or fuels • generally low-level to intermediate-level radioactive waste that must be stored for approximately 100 years [20; 17; 103]	• risk of accidents resulting in uncontrollable chain reactions and release of (highly) radioactive materials • high exposure to radiation with long half-lives, especially from spent fuel • ranges from low-level to high-level radioactive waste – if high-level, final disposal in Germany for up to 1 million years[7]

Table 1: The differences between nuclear fusion and nuclear fission

*radioactive

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[6] Boiling water reactors: approximately 290 degrees Celsius at 70 bars; pressurised water reactors (commonest reactor type worldwide): approximately 320 degrees Celsius at 160 bars; ranging to high-temperature reactors with temperatures of > 1,000 degrees Celsius [23; 24].

[7] Repository Site Selection Act, Article 1.2

2 Technological concepts and fuels

Most research into the use of nuclear fusion for energy production is focused on two fundamental technological approaches: magnetic confinement fusion and inertial confinement fusion. The latter primarily includes laser fusion. Both approaches can use essentially the same fuels and will be implemented as thermal power plants (see Figure 3). The nuclear fusion reaction generally releases neutrons that are decelerated and trapped by the plasma chamber’s first wall, converting their kinetic energy into heat. The heat is routed through a heat exchanger or circuit to produce steam, which is then used by turbine generators to generate electricity. [17; 25; 26; 20]

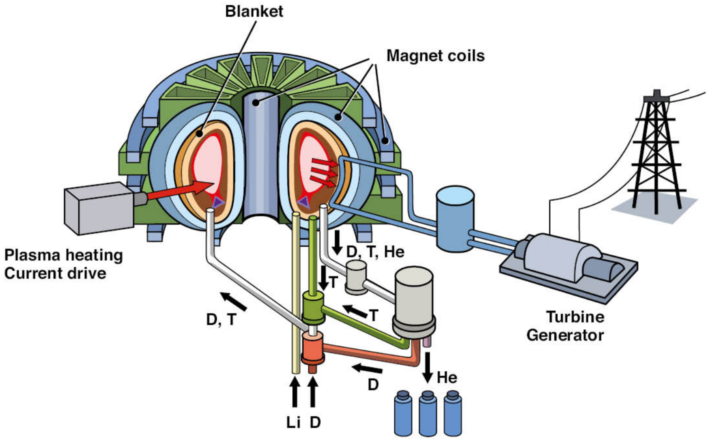

Figure 3: Fusion power plant design. The illustration shows a magnetic confinement fusion system with the materials used and produced in the nuclear fuel cycle: lithium (L), deuterium (D), tritium (T) and helium (He). Source: MPI for Plasma Physics, Karin Hirl [27]

2.1 Magnetic confinement fusion

In **magnetic confinement fusion** (MCF), the fusion fuel in the form of a plasma is confined within the reactor by means of strong magnetic fields. An external heating system heats it to over 100 million degrees Celsius for a few seconds until it ignites. Approximately 50 to 100 megawatts of power is momentarily supplied by the startup heating system to achieve ignition. [28] Once enough atomic nuclei fuse, sufficient heat is generated for the plasma to become self-sustaining and the heating systems can be switched off. As well as containing the charged plasma particles within the plasma chamber, magnetic confinement also prevents the plasma from touching the plasma chamber’s first wall. This would cause the plasma to cool very rapidly and lose its plasma state. The plasma could also damage the first wall if it came into contact with it. [21; 25; 26; 28] A longer confinement time at the same temperature level means that, unlike in inertial confinement fusion, the plasma does not need to be compressed.[8] [17]

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[8] The pressures in magnetic confinement fusion are about one hundred billion times lower than in inertial confinement fusion. The plasma pressure is in the range of 3 to 7 bars. The plasma chambers of magnetic confinement fusion reactors thus have a large volume of about 1,000 cubic metres. [17]

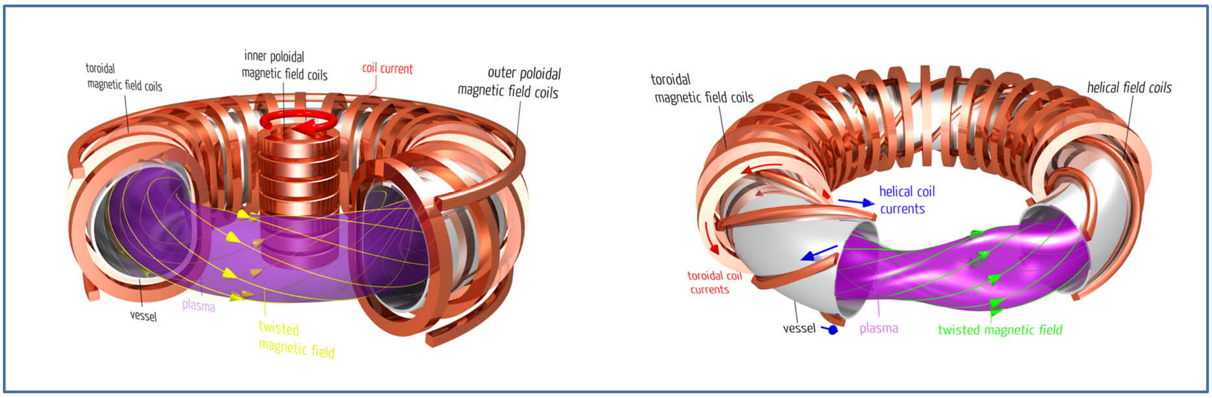

Figure 4: Design of a tokamak (left) and stellarator (right). Source: © Wengenmayr, R. | MPI for Plasma Physics/CC BY-NC-ND 4.0 [29]

At present, the two most promising magnetic confinement fusion reactor types are the **tokamak** and the **stellarator**. Both use magnets to confine the plasma in a toroidal (doughnut-shaped) plasma vessel. However, they differ with regard to the geometry of the magnetic fields inside the plasma vessel.

- In a **tokamak**, the plasma is confined by three superposed magnetic fields. The first magnetic field is generated by the magnetic coils surrounding the toroidal plasma vessel, creating a ring-shaped magnetic field (see Figure 4). A second magnetic field is needed to prevent the plasma from coming into contact with the reactor wall. This requires an electric current that runs through the plasma and is induced by a transformer coil inside the tokamak. The third magnetic field, which is generated by vertical coils, confines the plasma current from above and below. Although this technology has the advantage of a relatively simple design, after a while the transformer coil that induces the internal electric current must be switched off and on again. Consequently, steady-state operation of tokamaks is not currently possible – they must be periodically switched off and on in what is known as "pulsed operation". It is anticipated that pulses lasting several hours will eventually be achieved[9] and research ideas for enabling steady-state operation have also been proposed. [30; 31; 32; 33; 34]
- By contrast, the **stellarator** is capable of steady-state operation. The entire magnetic field is generated by external magnetic coils in a very specific arrangement, making a transformer coil unnecessary. However, the arrangement of the coils is so complex that it could only be designed with the aid of mainframe computer simulations. On the other hand, the plasma control requirements are somewhat less challenging. [35; 25; 36]

2.2 Inertial confinement fusion

In **inertial confinement fusion** (ICF), high-power lasers or ion beams focus the necessary energy onto a target. The targets are pellets of a few millimetres in diameter comprising the frozen fuels that will fuse together. This method is called inertial confinement fusion because inertia is critical to achieving plasma ignition (see Figure 5). It ensures that when the very short, intense burst of energy is fired at the target, the fuel under its outer layer is compressed enough to achieve the temperatures (> 100 million degrees Celsius), pressures (hundreds of gigabars) and densities (> 1,000 times solid density) needed to ignite the plasma.

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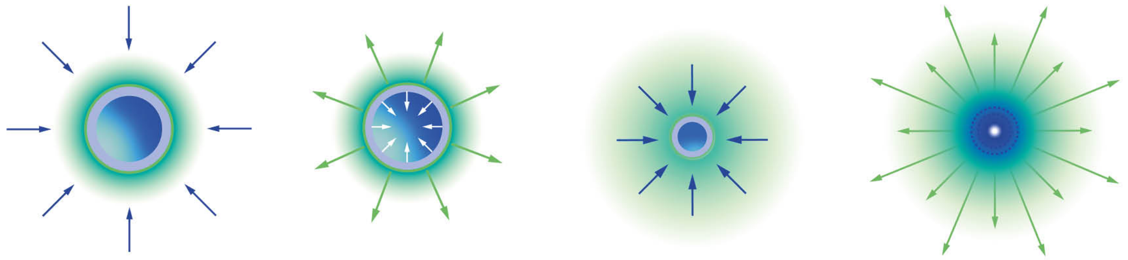
[9] The electric current in the primary winding of a transformer must be an alternating current in order to induce a voltage. But this current can only be increased for a limited time before it must be interrupted by switching it off and on again or reduced in a targeted manner. The ambition is to achieve pulse lengths of around 1 to 2 hours for demonstration and commercial tokamak-based power plants [30; 31]. By modifying the plasma heating mechanism (electron cyclotron current drive; lower hybrid current drive) it may in future be possible for tokamaks to achieve a constant plasma flow, potentially enabling steady-state operation [32; 33; 34].

Unlike magnetic confinement fusion, the conditions required for fusion are only achieved for a very short time, usually just a few nanoseconds. [17; 37]



1
Laser irradiation

Laser or particle beams (blue arrows) cause a plasma envelope to form very rapidly around the surface of the fuel pellet.

2
Rocket effect

The outer part of the shell explodes outwards (green arrows). The recoil principle creates a pressure wave (white arrows) that heavily compresses the fuel inside the pellet.

3
Compression

The pressure (blue arrows) causes a huge increase in the fuel's density and temperature, creating the conditions to ignite the nuclear fusion reaction in the pellet core.

4
Ignition

After ignition, the plasma burn spreads through the whole pellet releasing fusion energy (green arrows) many times greater than the input energy.

Figure 5: The inertial confinement fusion (ICF) process. Source: Illustrations from FOCUSED ENERGY [38] with adapted text.

Current research is pursuing **a number of different basic concepts** and approaches to inertial confinement fusion. While the indirect drive (IDD) process is the most advanced, other approaches being investigated in test facilities include direct drive (DD), fast ignition (FI) and shock ignition (SI). [17; 21; 39]

- In the **indirect drive** approach, the target is inside a shell. The laser beams enter the shell, the so-called hohlraum, through openings in its walls, generating blackbody radiation (X-rays) when they hit its inner wall. This radiation uniformly compresses the target until it ignites.
- In the **direct drive** approach, the laser beams strike the fuel pellet directly from all sides. In order to achieve the uniform compression required for ignition, the energy must be distributed symmetrically – the beams must hit the fuel pellet very precisely from all sides at the same time. [40; 17]
- **Fast ignition** decouples the compression and ignition phases that are induced by laser or energy pulses. The nuclear fusion reaction is initiated by a separate pulse that is delivered directly inside the pre-compressed target through a hole or “cone”.
- In **shock ignition**, compression is also carried out separately using laser pulses. Ignition is then initiated by a second, short, high-intensity pulse that, unlike in fast ignition, hits the outer surface of the target rather than being delivered directly inside it.

2.3 Fuels

The same fuels can be used in both magnetic and inertial confinement fusion. As the number of protons in the fuels' atomic nuclei increases, the repulsive electric forces between the nuclei get stronger, meaning that more initial energy is required to overcome them. The most reactive nuclear fusion reaction with the lowest requirements in terms of the relationship between plasma temperature, confinement time and pressure is between the two hydrogen isotopes[10] **deuterium** (D/^{2}H) and **tritium** (T/^{3}H). [41] Consequently, these are the most widely used **fuels** in fusion experiments, and expert opinion currently regards them as the likeliest candidates for use in fusion power plants. No other nuclear fusion reaction's reaction rate peaks at such "low" temperatures (see). The deuterium-tritium reaction also achieves the highest theoretical ratio of energy output to input. [17; 42; 43]

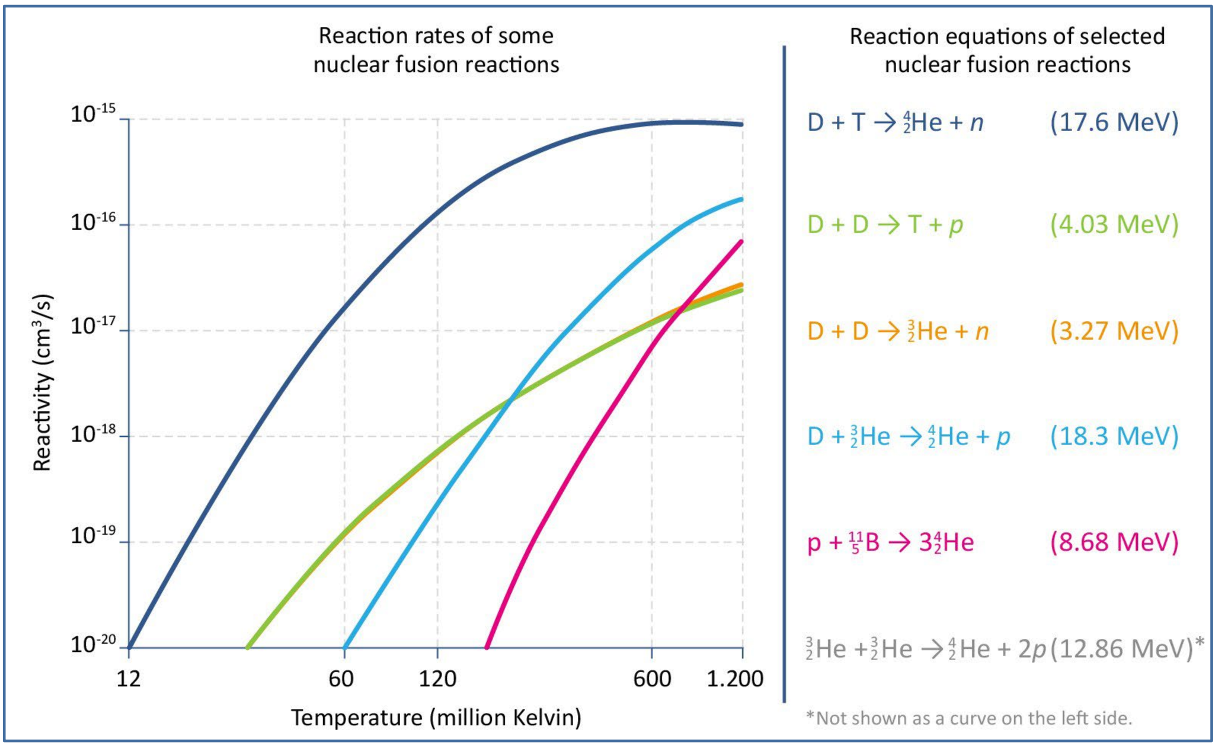


Figure 6: Reaction rates of nuclear fusion reactions with different fuels plotted against temperature (left) and reaction equations for the most widely researched nuclear fusion reactions (right). Source left: adapted from Haefner et al. 2023 [17]; source right: Meschini et al. 2023 [42]

Other possible nuclear fusion reactions are the reaction between two **deuterium atoms** (D+D), the reaction between two **helium atoms** (He+He), and the reaction between **deuterium and helium** (D+He). Especially when the reaction between the fuels releases 14.1 megaelectron volt neutrons (n), as in the reaction between deuterium and tritium, materials inside the plasma chamber can be damaged and activated, making them radioactive.

---

[10] A simple hydrogen atom has just one proton in its nucleus. The nucleus of deuterium, also known as heavy hydrogen, contains one proton and one neutron. Tritium, or "super-heavy hydrogen", has a second neutron in its nucleus. Some 99.99% of the naturally-occurring hydrogen on Earth is simple hydrogen. Just 0.015 percent of naturally-occurring hydrogen is deuterium, while the figure for tritium is far lower still (10^{-15} percent). [41]

In some nuclear fusion reactions such as the reaction between hydrogen (^1H) and boron (also known as the **proton-boron reaction** (p+B)[11]) or the fusion of Helium-3 (^3He) nuclei, no neutrons are released in the initial reaction. However, these reactions are not completely aneutronic, because there is a small possibility that neutrons will be produced by other processes occurring in parallel. Moreover, the proton-boron reaction has one major drawback. It requires much more energy to ignite the plasma than the deuterium-tritium reaction due to the higher number of protons in the boron nucleus. The temperature needed to initiate the nuclear fusion reaction is thus 10 to 30 times higher (1 to 3 billion degrees Celsius as opposed to 100 million degrees Celsius [44; 45]). This results in correspondingly higher bremsstrahlung losses that cause the plasma to cool.

In magnetic confinement fusion, the higher temperatures also place higher demands on the materials used in the reactor core. [17; 42; 43] Because the temperatures needed for the proton-boron reaction are at least 10 times higher and the reaction rates are significantly lower (see Figure 6), the triple product (see 3.2) of particle density, confinement time and temperature must be about 1,000 times higher than for the deuterium-tritium reaction. Consequently, the experts are currently rather sceptical about the proton-boron approach's feasibility.

---

[11] The four helium atoms produced in the proton-boron reaction have a lower mass number (4) than the boron (mass number 11) fuel. However, the fact that a carbon atom (mass number 12) is formed for a very short time means that it is still a nuclear fusion reaction. The carbon atom exists in such a highly excited state that there is a very high probability of it rapidly decaying into four helium atoms, with the energy being transferred into the helium atoms' kinetic energy.

3 Current state of the technology

Various indicators can be used to determine how much energy is produced or could be supplied by nuclear fusion reactions and how advanced the necessary technology is. The technology readiness level (TRL) methodology uses a scale to describe technologies' different stages of development.[12] In principle, this method can be applied to the readiness level of individual components or elements, of different technological approaches (magnetic confinement fusion, laser fusion), or of entire fusion power plants. [46; 47; 48; 49; 50] Meanwhile, the triple product and the energy balance provide an indication of whether fusion will be achieved, whether it will be sustained without an external energy input, and how much net energy it will produce (see Figure 7).

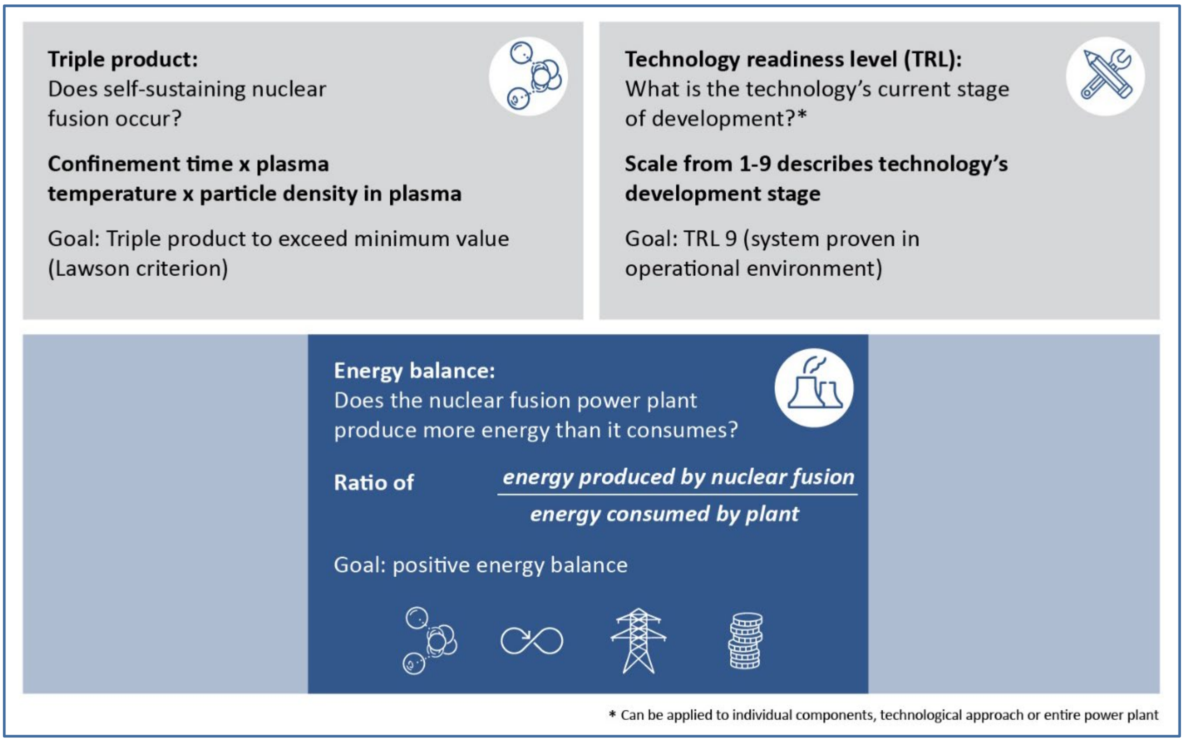


Figure 7: Indicators for maturity of fusion research with the ultimate goal of producing energy; Source: authors' own illustration

3.1 Technology readiness level

Harnessing nuclear fusion to produce energy is a complex and challenging endeavour. The different approaches have been investigated to different extents and for different lengths of time, and this is reflected in their different stages of development. However, no approach has yet definitively made it past the laboratory testing stage (TRL 5).

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[12] The different technology readiness levels describe the development and rollout of a technology or invention, from the basic research stage (TRL 1) to the commercial end product (TRL 9). [46; 47] For an overview, see e.g. [48]. It is important to remember that technologies are assigned a TRL based on the assessments of experts, who may not always agree with each other. Assigning a technology to a particular stage says nothing about how long it will take to reach the next stage. Furthermore, no specific nuclear fusion TRL criteria currently exist for determining the maturity level of the technological approaches, materials and power plant components. [49; 50]

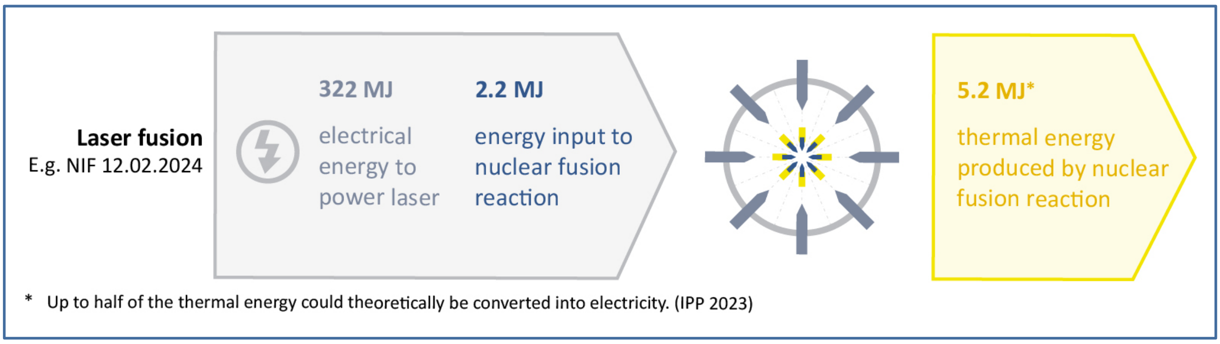
- In the field of **magnetic confinement fusion**, the **tokamak** is currently considered to have achieved a somewhat higher technology readiness level. At present, it is somewhere between TRL 4 and 5, i.e. between the “technology validated in lab” stage (4) and the “technology validated in relevant environment” stage (5). The tokamak has hitherto attained higher triple product values and technology readiness scores than the **stellarator**, which is generally deemed to be somewhere between TRL 3 (experimental proof of concept) and TRL 4 (technology validated in lab). [50, 51, 52] It is important to note that certain individual components or aspects of the different solutions may be more or less advanced than the overall score suggests. For instance, the magnet configurations and heating systems for the tokamak and stellarator are very advanced, and plasma performance is well understood. On the other hand, the fuel cycle design for both magnetic and inertial confinement fusion has a lower TRL. [50; 52] If successfully implemented, the planned ITER (International Thermonuclear Experimental Reactor, tokamak) research reactor will be in the region of TRL 6 (prototype). ITER’s planned successor DEMO (DEMOnstration Power Plant, tokamak or stellarator) would then move up to TRL 7 (demonstrator).
- **Inertial confinement fusion** techniques were developed somewhat later than magnetic confinement fusion. They remained a military secret for many years because the experiments with this technology also have military applications, such as helping to improve understanding of the processes involved in hydrogen bombs. [53; 54; 55; 56] The different laser fusion approaches are at different stages of development. The indirect drive approach is the most advanced (TRL 3 – experimental proof of concept), followed by the direct drive method (TRL 2 – technology concept formulated). However, the fast ignition and shock ignition approaches are still at TRL 1 (basic principles observed). [17]

3.2 Plasma stability and energy balance

The primary requirement for the technical implementation of nuclear fusion is a **self-sustaining fusion** reaction. This occurs if, after the initial external energy input, the plasma is subsequently heated by the first fusion events and the energy released leads to a further increase in fusion events. These compensate for the energy losses that result, for example, from radiation or particle losses. For a self-sustaining fusion reaction to occur, the product of the plasma confinement time, the particle density in the plasma and the plasma temperature (triple product) must exceed a certain threshold known as the Lawson criterion (see 1.1).

While the Lawson criterion describes the physical conditions that must be met to achieve ignition of the plasma, the ratio of energy released from the fusion reaction to energy input into the plasma (for magnetic confinement fusion) or into the reactor (for inertial confinement fusion) is also crucial. These ratios ultimately determine the overall energy balance of the experiment or, in perspective, of the reactor or power plant. At present, fusion processes still produce far less energy than the energy needed to power an entire test reactor or a power plant (see Figure 8 and Figure 9).

Researchers got progressively closer to achieving self-sustaining fusion over the past few decades, until a **laser fusion experiment** at the National Ignition Facility (NIF) in the United States exceeded the Lawson criterion in a controlled laboratory-scale fusion reaction for the first time in 2021. The experiment used the indirect drive method to heat and compress a central "hot spot" of deuterium-tritium fuel. [57] A subsequent NIF experiment reached another important threshold on 5 December 2022: for the first time, a self-sustaining nuclear fusion reaction was able to generate more energy than was previously delivered directly to the target. In this case, the energy losses that occur between the entry of the laser energy into the reactor chamber and the coupling of the energy into the target were also compensated for. With 3.15 megajoules of heating energy, 1.53 times more energy was released than was injected into the target by the laser (2.05 megajoules). Further repetitions of the experiment increased this ratio by up to 2.36 times (5.2 megajoules when using 2.2 megajoules – see Figure 8). No other fusion test facility has yet achieved a comparable fusion gain. [58; 59]

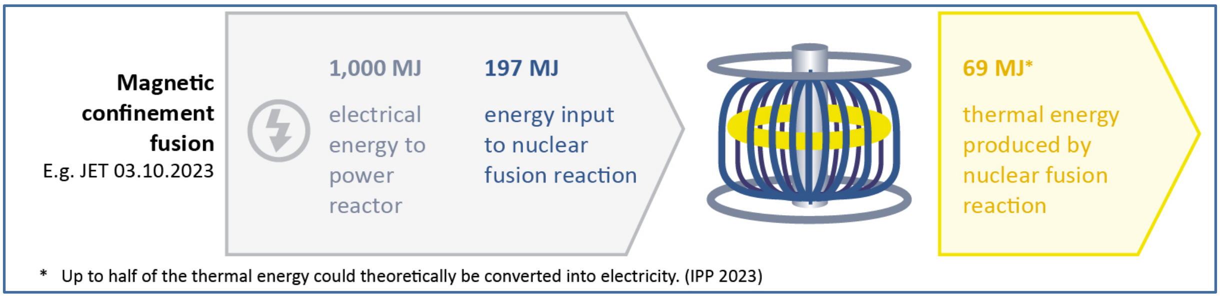


* Up to half of the thermal energy could theoretically be converted into electricity. (IPP 2023)

Figure 8: Energy balance of a laser fusion experiment. Source: authors' own illustration using data from Osolin [59], Simpson [60] and expert input from EURO fusion and the Fraunhofer Institute for Laser Technology (ILT)

The magnetic confinement fusion approach has yet to meet the Lawson criterion. With this technology, a certain ratio between the surface area and volume of the confined plasma is needed to compensate for the heat losses. This ratio will likely only be achieved with the ITER reactor currently under construction in Europe or with SPARC in the USA. SPARC is being built as part of a collaboration between the Massachusetts Institute of Technology (MIT) and the startup Commonwealth Fusions Systems. Both test reactors are designed as tokamaks. [43; 26; 42] The JET test reactor achieved the best result to date in terms of the amount of energy generated in the field of magnetic fusion shortly before it was decommissioned at the end of 2023: As a side effect of experiments on the controllability of the plasma, 69 megajoules of fusion energy were released in October after 197 megajoules of heating energy were introduced into the plasma (see Figure 9).

In 2020, ITER's first plasma ignition was still scheduled for 2025, but it has now been pushed back to 2034, initially using deuterium-deuterium reactions. Fusion operation is scheduled to begin with this fuel combination in 2035, before moving to the deuterium-tritium operation phase in 2039. However, even ITER will not achieve a positive overall energy balance, since the reactor is too small and was not designed for this purpose. The intention is for this step to be achieved by its successor, the DEMO demonstration reactor.[13] [26; 61; 62; 63; 64; 65; 66] The smaller SPARC test reactor has an ambitious timeline and is currently expected to begin operating in 2026. [67; 68]



* Up to half of the thermal energy could theoretically be converted into electricity. (IPP 2023)

Figure 9: Energy balance of a magnetic confinement fusion experiment. Source: authors' own illustration using data from IPP [69] and expert input from EUROfusion.

It is thus evident that the ratio of thermal energy produced to initial energy input into the reactor must still increase substantially before an operational power plant can be realised. The overall **energy balance** that compares a plant's total energy demand against the energy that the plant produces from the fusion reaction is thus key to the development of an operational and – eventually – commercially viable fusion power plant. [17; 70]

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[13] The DEMO (tokamak or stellarator) reactor will incorporate the lessons learned from operating ITER and from other tokamak and stellarator research projects. The aim is for this demonstration reactor to have all the components and functions of an operational power plant. This includes a closed fuel cycle, meaning that DEMO will produce the tritium it needs on site. This first-of-a-kind power plant is due to start supplying electricity to the grid in around 2050. [26; 63; 64; 65; 66]

4 Nuclear fusion projects around the world

The International Atomic Energy Agency (IAEA) lists 144 fusion projects around the world (Figure 10). These are being carried out by a range of actors – mainly research institutions (around 75 percent), but also startups. The projects are also at different stages in their development (in/not in operation, under construction, being planned).[14] [71; 72] The countries with the most facilities are the USA (35), Japan (25), Russia (13), China (11) and the United Kingdom (9). There is a total of 21 projects in the EU, 4 of which are in Germany according to the IAEA. [72]

Figure 10: Regional distribution of different fusion facility types as per IAEA. Source: adapted from FusDIS 2021 [72]

4.1 Research institutions

As far as **magnetic confinement fusion** projects are concerned, there are currently 56 **tokamak** research facilities in operation worldwide, 10 of them in Europe. [72] At present, the world's largest tokamak is the JT-60SA, a joint project between Japan and the EU. In 2023, it took over this title from the European JET facility, which operated between 1983 and 2024 and in 1991 became the first to produce a significant amount of energy from a controlled nuclear fusion reaction. JET delivered a fusion power of approximately 1.7 megawatts for two seconds. [73; 74; 75] JT-60SA is a "satellite project" that supports the research carried out at ITER and for DEMO. It is helping to investigate various questions, such as safety aspects relating to the interaction between different components, ways of increasing pulse duration and plasma scenarios. Plasma scenarios are modes of operation of a power plant that enable maximum thermal insulation of the plasma while maintaining plasma stability. The scenarios are being developed for use with ITER. [76; 77] On 30.12.2021, China's Experimental Advanced Superconducting Tokamak (EAST) maintained a stable plasma in pulsed operation for a record time of 1,056 seconds. [78] EAST was built in partnership with the Russian Federation in the 1990s. Since its structure is similar to ITER's, the plasma physics research being conducted there is also contributing to ITER's development. [79]

As already mentioned, **stellarator** research is not as advanced as tokamak research. Consequently, the initial objective of Wendelstein 7-X – which has been in operation in Greifswald since 2015 and is currently the world's largest and most powerful stellarator – is to investigate the stellarator concept's fundamental

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[14] It should be noted that the IAEA does not distinguish between research facilities that are in operation and those that are inoperative. Moreover, their data does not always match other sources. For instance, the Fusion Industry Association lists 43 startups, whereas the IAEA lists 33. [71; 72 – Retrieved: 25.03.2024]

suitability for a power plant. This includes aspects such as plasma generation and particle and energy confinement in the plasma. [80; 81] On 15 February 2023, Wendelstein 7-X set a new record for plasma confinement in a stellarator when it achieved a plasma discharge time of around 8 minutes. [82] There are currently 12 stellarator-like devices in operation around the world. [72] In addition to Wendelstein 7-X, Europe has a number of smaller research stellarators in Germany, Ukraine and Spain. Japan's Large Helical Device (LHD) is the largest stellarator outside Europe, while there are smaller devices in the USA and Costa Rica. Broadly speaking, the different test facilities differ in aspects such as their magnetic field configurations. This means that they can be compared against each other (in terms of plasma properties, plasma confinement, etc.) and against the tokamak approach. [79; 83] However, none of them yet aims to produce a self-sustaining nuclear fusion reaction – this is something that no stellarator has ever achieved.

The main centre of magnetic confinement fusion research in Germany is the Max Planck Institute for Plasma Physics (IPP). The ASDEX Upgrade (tokamak) in Garching and the Wendelstein 7-X in Greifswald are two of the most important magnetic confinement fusion research facilities in Germany. The ASDEX Upgrade has been in operation since 1991 and is used for basic research. It delivers important insights for plasma operation at the ITER international test reactor and for potential tokamak power plants in general. The ASDEX Upgrade facility's main research focus is plasma scenarios and the use of a divertor to remove particles and heat.[15] It is the only device in the world to use the promising material tungsten for the reactor core's first wall. [84; 85] Forschungszentrum Jülich and the Karlsruhe Institute of Technology (KIT) are two other significant magnetic confinement fusion research institutions in Germany.[16] [86]

According to the IAEA, there are currently fewer than 10 **inertial confinement fusion** research facilities in operation. They are located in the USA, Japan, China, the United Kingdom and France. [79; 17] The NIF at the Lawrence Livermore National Laboratory (LLNL) is currently the only facility in the world with lasers powerful enough to achieve plasma ignition that spreads through the target. [17] Other research institutions with very powerful lasers are located in France, the USA and China. Based on current knowledge, it is expected that, once completed, Russia's UFL-2M laser fusion facility will have one of the world's most powerful laser systems, comparable to the NIF. [17; 87] It is important to bear in mind that the research pursued at the NIF, France's Laser Mégajoule (LMJ) and Russia's UFL-2M is primarily for military purposes rather than energy applications. [88; 89; 17; 90; 91] The inertial confinement fusion research landscape also includes various other research institutions working together through structures such as LaserNetUS in the USA [92] and both Laserlab Europe [93] and the Extreme Light Infrastructure [94] in Europe. Z-pinch is another inertial confinement fusion approach where an electric current induced in the plasma creates a magnetic field that compresses the plasma. Sandia National Laboratories in the USA is one of the organisations investigating this approach. [95]

At present, there is relatively little inertial confinement fusion research in Germany and there are no implosion research facilities with lasers comparable to the National Ignition Facility (NIF) in the USA or the LMJ in France. However, several research institutions and companies are working on topics such as shock physics, particle acceleration and optics, manufacturing and plant engineering, and the surface properties and robustness of materials under extreme conditions. Others are involved in laser fusion research through their internationally important high-power laser systems, precision measuring instruments or expertise in

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[15] The divertor diverts impurities that come off the reactor wall and the waste products of the nuclear fusion reaction (e.g. helium) away from the vacuum vessel's interior. The divertor thus regularly comes into direct contact with the plasma.

[16] The Forschungszentrum Jülich focuses mainly on interactions between the plasma and the first wall and on the suitability of different materials for the reactor core. Research topics at KIT include neutron-resistant materials, material toxicity, the production of tritium in breeding blankets, closing the tritium fuel cycle, and divertor concepts. [86]

target production. Some research institutions in Germany are also working on laser plasmas and laser plasma diagnostics.[17]

4.2 Startups

In 1992, Princeton Fusion Systems in the USA became the first startup in the field of nuclear fusion. It would be followed by TAE Technologies in 1998 and General Fusion in 2002. While the number of fusion startups then grew slowly but surely to 12 in 2017, it has undergone a marked increase since 2018. There are currently 43 startups, most of which are in the USA (25), followed by Europe (9), Asia (5), and Australia, Israel, Canada and New Zealand (1 each). [71; 71]

One difference between the startup community and research institutions is that some startups are working to very ambitious schedules, with plans to build the first power plant before 2040. Most experts are sceptical about this timeframe (see Chapter 7). Another difference is that the startups are pursuing a wider range of technological approaches that they hope will enable the commercialisation of nuclear fusion. [72; 79; 71; 112; 72; 79] For instance, they are working on concepts that are no longer being specifically pursued by research institutions, such as the field-reversed configuration magnetic confinement design. While this concept was initially developed by researchers, it was superseded by the more promising tokamak and stellarator approaches. However, it has been revived by Princeton Fusion Systems and TAE Technologies. [96; 112; 71; 79] Other startups are investigating approaches that are still in the earliest stages of development. Focused Energy and EX-Fusion (Japan), for example, are both pursuing the fast ignition approach to inertial confinement fusion. (38; 97; 71; 112]

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[17] As well as research institutions like the Helmholtz-Zentrum für Schwerionenforschung (GSI), the Fraunhofer Institute for Laser Technology (ILT), the Laser Zentrum Hannover (LZH), the Max Planck Institute of Quantum Optics (MPQ) and the Helmholtz-Zentrum Dresden-Rossendorf, these also include universities such as Ludwig-Maximilian-Universität München (Centre for Advanced Laser Applications (CALA)), TU Darmstadt (Institute for Nuclear Physics), the Technical University of Munich (Department of Physics) and the University of Stuttgart (Institute of Laser Technologies (IFSW)), and companies like TRUMPF, IPG, Jenoptic and Zeiss. [21; 17]

INFO: Startups in Germany

Magnetic confinement fusion

Gauss Fusion

Founded	2022
Based in	Garching
Approach	stellarator fuels: deuterium and tritium
Goal	commercial gigawatt-class power plant by 2045

Sources: Gauss Fusion n.d..; Presseportal 2024; FIA 2023

Proxima Fusion

Founded	2023
Based in	Munich
Approach	stellarator – IPP spin-off with Wendelstein-7-X experience fuels: deuterium and tritium
Goal	pilot plant by early 2030s and commercial power plant by end of 2030s

Sources: Proxima Fusion n.d.; FIA 2023

Laser fusion

Marvel Fusion

Founded	2019
Based in	Munich
Approach	short-pulse laser-driven inertial confinement fuels: unspecified
Goal	pilot plant by 2032; commercial power plant from mid-2030s

Sources: Marvel Fusion n.d.; Astheimer/Finsterbuch 2023; FIA 2023

Focused Energy

Founded	2021
Based in	Austin, Texas (USA)/Darmstadt
Approach	laser-driven inertial confinement fusion (fast ignition direct drive) fuels: deuterium and tritium
Goal	pilot plant by second half of 2030s

Sources: Focused Energy n.d.; Ditmire et al. 2023; FIA 2023

Most startups have followed the research institutions in opting for deuterium and tritium **fuel**, since this makes it easier to achieve the conditions required for nuclear fusion. [71] However, in order to avoid radioactive waste (see 2.3 and 6.4), some are pursuing or have previously pursued other approaches – which includes the reaction between (hydrogen)protons and boron – that are more challenging in terms of achieving fusion conditions (e.g. Marvel Fusion, TAE Technologies). [44; 45]

According to Fusion Industry Association data, the startups are almost entirely **funded** by private investors (about 98 percent). The total amount invested up to 2022 came to approximately 6.2 billion US dollars, an increase of 1.4 billion US dollars from 2021 alone.[18] [76; 98] However, this funding is far from evenly distributed. Eight of the startups have raised more than 200 million US dollars each, with Commonwealth Fusion Systems (over 2 billion US dollars) and TAE Technologies (over 1 billion US dollars) accounting for slightly more than half of the 6.2 billion US dollar investment total between them. [71]

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[18] By way of comparison, the cost of ITER, the largest and most expensive fusion project to date, is currently estimated at around 18-22 billion euros. [28] However, the test reactor's special cost structure and the fact that it has to reflect the interests of multiple project partners from around the world [28; 98] means that the project is not really comparable to projects focused solely on the construction of a fusion power plant.

5 Opportunities and benefits of fusion research

The main factor driving the development of nuclear fusion is the prospect of secure, net-zero energy production that is not weather-dependent. Fusion power could supplement renewable energy as a means of generating electricity, help to reduce global reliance on fossil fuels and strengthen Europe's energy sovereignty. Since fusion power plants will mostly be centralised plants in the gigawatt range (probably 1-2 gigawatts of electrical output; comparable to today's nuclear and coal-fired power plants[19]), [99] they could be used in a similar way to existing large fossil fuel or nuclear fission power plants. As well as helping to meet the general rise in electricity demand associated with electrification and digitalisation, commercially competitive fusion plants could supply future applications such as electrolytic hydrogen production, seawater desalination and potentially also the removal of CO_2 from the atmosphere by Direct Air Capture (DAC) (for more on this, see Chapter 8). [21; 17; 100; 101; 20]

Nuclear fusion has some advantages that are frequently cited in the debate concerning the prospects of its implementation and integration with the energy system. These benefits include the fact that prospective fusion power plants would require less space than other forms of energy production and would be less harmful to the environment than fossil fuel power plants, especially due to their lower CO_2 emissions. The economic opportunities are also highlighted, for example the chance to unlock new markets and strengthen German and European industry if nuclear fusion is successfully implemented there.

5.1 Limited environmental impacts

Various reasons are commonly put forward to support the argument that nuclear fusion has **fewer environmental impacts** than other forms of energy production. Compared to nuclear fission power plants, there is less risk from radioactive fuel and reaction products. Compared to fossil fuels, the production of electricity in fusion plants has lower emissions, and in general the plants require less space for a given generating capacity.

Unlike the spent fuel from nuclear fission plants, the radioactive waste from fusion plants is only high-level if certain materials are used in the reactor core. Most fusion reactors only generate **low-level to intermediate-level radioactive waste** that doesn't need to be stored for an extremely long time (final disposal). The waste from fusion reactors must only be safely stored for around 100 years. As well as the lower waste impacts compared to nuclear fission, there is also no fundamental risk of a chain reaction with nuclear fusion. There is thus no danger of major nuclear accidents – if a radiation incident did occur, its impacts would be confined to the fusion plant site and its immediate surroundings. Other positive aspects include the **small amounts of fuel needed**, especially compared to fossil fuel power plants, and the potentially greater availability of fuel compared to nuclear fission plants, reducing dependency on fuel suppliers. [102; 17; 20; 103]

The **CO_2 emissions** from operating a fusion power plant are significantly lower than those of fossil fuel power plants. Most of the CO_2 emissions in a fusion power plant's entire life cycle are associated with the plant's construction and decommissioning and the safe storage of the radioactive waste. And even these emissions will fall steadily as we move towards a low-carbon economy. Life cycle assessments currently calculate that the level of emissions from fusion power plants is broadly similar to wind farms, solar farms

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[19] Magnetic confinement fusion power plants in particular will probably have an output in this range, but a handful of developers are also working on smaller reactors. Using a mix of magnetic and inertial confinement fusion, the startup General Fusion is planning an initial power plant with an electrical output of approximately 300 megawatts, composed of two 150 MW_e machines running in tandem. [99]

and nuclear fission plants. [101; 104; 105; 106] The main waste gas from nuclear fusion reactions is helium, which is not classified as a greenhouse gas and is non-toxic to humans and the environment. [20; 107; 108]

Essentially, a fusion power plant requires a similar amount of **space** to a fission power plant. [109] According to life cycle assessments, fission plants currently use the least space per unit of output, with current figures similar to onshore wind and roof-mounted solar panels. [105]

5.2 Economic opportunities and high-tech development

The development of a fusion power plant would not only be a useful addition to the future German and European energy systems. As long as fusion power plants can be commercially competitive in the cross-sectoral energy system, there will also be other benefits for countries with fusion technology know-how. With global electricity demand expected to rise significantly, **new export markets could be unlocked** for the developed technological systems and the know-how to install them as well as for the relevant components. The rollout of this new technology could thus help to strengthen the appeal and competitiveness of German and European industry as well as reducing reliance on energy imports. [17; 21; 70; 110; 111]

While most work to develop nuclear fusion is still at the basic research stage, a handful of solutions have already reached the applied research stage. [17; 21; 42] Spillover effects and spin-offs arising from the development of high-tech components can spread the risk for investors and could help to strengthen Germany's technology sector and the domestic supplier industries. While electricity generation remains the main focus of nuclear fusion startups, they also see potential to generate revenue from the use of technological solutions, materials and analysis methods in other areas of application such as medicine, optics, diagnostics, robotics and space travel.[20] [17; 21; 42; 71; 86; 112; 113]

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[20] For example, the second oldest nuclear fusion startup, TAE Technologies, has around 1,400 registered patents worldwide [112], while Princeton Satellite Systems, the parent company of Princeton Fusion Systems (founded in 1992) is active in the field of spacecraft control systems. [113]

6 The challenges in building a nuclear fusion power plant

None of the different fusion concepts has yet developed to the stage where an operational test power plant could be built. Several challenges must still be overcome before the technology can be realised and achieve commercial viability at a power plant scale. These include various technical challenges relating to the plasma chamber design, the power of the lasers or magnets, the development of sufficiently robust materials, closing the fuel cycle and the industrial-scale production of the fuel targets. Extensive research is also being carried out into the automation of processes for feeding fuel into the plasma chamber, remote maintenance and changing components subject to extremely high stresses. There are also various regulatory and funding issues that must be resolved for all of the concepts. These challenges are essentially the same for the research institutions and startups (see also Figure 11) working in this field. [70; 114; 17; 21; 71]

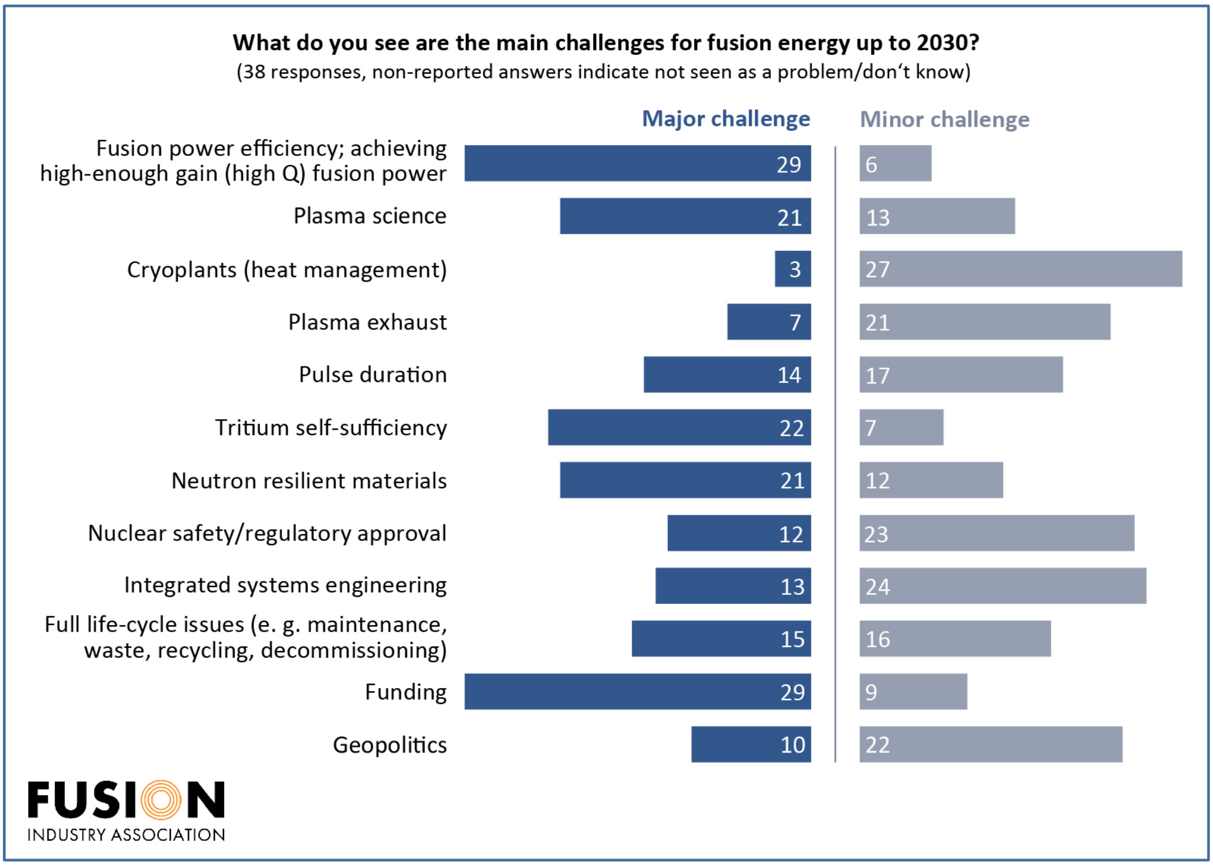

Figure 11: Main challenges for nuclear fusion up to 2030 as reported by startups. Source: adapted from Fusion Industry Association 2023, p. 12 [71]

6.1 Plasma stability and energy balance

In order to achieve continuous energy production, the **conditions required for nuclear fusion** must be reliably maintained for a long period of time or repeated at a high frequency. To operate a commercially viable magnetic confinement fusion power plant, the plasma would need to be kept stable for several hours or even days. This is much longer than the current records, which stand at no more than a few minutes[21], although it should be borne in mind that large-scale experiments are to some extent limited by technical

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[21] Currently around 17 minutes for the tokamak and around 8 minutes for the stellarator (see 4.1).

constraints, for example with regard to the supply of sufficient energy. As well as the need to increase the power of the energy pulse delivered to the target, the key challenge for inertial confinement fusion is to increase the shot rate. At present, it is only possible to achieve a few shots a day, and the lengthy cooling-off period required by the highest-energy lasers means that they can only manage one shot every two days. An operational power plant, however, would need a shot rate of 10 to 20 shots per second.[22] [115]

Unless there is a significant increase in the plasma confinement time of magnetic confinement fusion systems or the shot rate and intensity of inertial confinement fusion systems, it will not be possible to achieve the stable fusion conditions that are key to attaining a positive **energy balance**. A severalfold improvement in the energy balance will be necessary for a commercially viable fusion power plant.[23] The energy balance refers to the total net energy yield, i.e. the difference between the power plant's total energy consumption and losses and the energy that it produces. In order to optimise the energy balance, it will thus not only be necessary to achieve the fusion conditions required for a power plant as described above, but also to concurrently develop material and technological solutions (see 6.2 and 6.3) that enable energy-efficient operation of the necessary components and power plant elements. In magnetic confinement fusion, for example, particularly large amounts of energy are needed to heat the plasma and cool the superconducting magnet coils (cryostat). [26; 116; 201] The main challenge for laser fusion systems, on the other hand, is the energy-efficiency of the laser. [17]

6.2 Technological components

The extreme environment inside the reactor and the high temperature differences that can occur are not the only design and development challenges for a fusion power plant's technological components. Another key issue is the lack of empirical knowledge, since it has not yet been possible to test some components and materials in a potentially realistic operating environment.

One particular challenge relates to the technical **design of the first wall**, i.e. the inner shell of the vacuum vessel, **and of the blanket**, which has to perform multiple functions at the same time. One question that needs to be addressed is how the heat generated by the absorption of the kinetic energy from the neutrons and atoms produced by the fusion reaction can be transferred as efficiently as possible from the blanket to the outer part of the power plant by a coolant. Potential coolants proposed in this context include water, helium or mixtures of helium, lithium and lead. The blanket walls must be engineered to be highly neutron-resistant in order to shield the outer parts of the device from neutron radiation. Another area of research is the production of tritium fuel through interactions with neutrons inside the blanket, as well as methods of extracting the tritium produced in this way for purification. This is important for approaches that use tritium as a fuel. [17; 20; 102]

A further challenge for inertial confinement fusion in particular is to identify the best vacuum technology for rapidly and efficiently extracting the reaction products from the blanket. This is because every plasma ignition requires a sufficiently clean ignition environment. In a commercial inertial confinement fusion power plant, the ash and any residual fuel inside the reactor would need to be removed after every shot, i.e. 10-20 times a second, in order to prevent any negative impact on the propagation of the laser beams. [17, 68]

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[22] The lasers typically have a pulse length of a few nanoseconds or less. [40; 17]

[23] For an inertial confinement or magnetic confinement fusion power plant to supply electricity to the grid at a commercially viable cost, the thermal energy produced by the nuclear fusion reaction would need to be roughly 50 times or more greater than the energy delivered to the target.

Magnetic confinement fusion reactors need powerful magnetic fields with large volumes (see e.g. [117]). Although significant advances in **magnet** performance have already been achieved, further improvements are still needed. For example, researchers are investigating ways of detecting thermomagnetic instabilities more precisely and damping them more effectively, since they can cause quenching of the superconducting magnets. Other research topics include improved heat load removal from the superconductors and more sophisticated deployment of low- and high-temperature superconductors in order to reduce the cooling power required by the system as a whole. [118; 42] More generally, the superconducting coils need to be adequately shielded from the high temperatures in the reactor core (over 100 million degrees Celsius) and the waste heat in and around the reactor. This is because they only become superconductive when cooled to extremely low temperatures (approximately -263 degrees Celsius in traditional superconductors). Researchers are also looking at how to reduce the magnets' overall volume and weight and bring down the cost of producing them. [118; 119; 65; 120; 65] The Massachusetts Institute of Technology (MIT) and the startup Commonwealth Fusion Systems have developed, tested and demonstrated a high-performance (20 Tesla) superconducting magnet for a tokamak that does not require such low temperatures and is more efficient. One key feature of this solution is that the superconducting tapes are not insulated. This reduces the magnet's volume and weight while also simplifying the superconductor's fabrication. [65; 121]

Further advances in **laser** technology will be vital for the laser fusion approach. The lasers used have a pulse length of a few nanoseconds. Each pulse must deliver enough energy to the target to achieve a positive overall energy balance with every shot. Modern pulsed diode laser systems are already about 10 times more efficient than the NIF system. In addition to increasing the shot rate as mentioned above, researchers are also investigating ways of increasing the pulse energy, improving laser focusability and optimising the laser light's wavelength and bandwidth. A high-precision system comprising multiple mirrors, lenses and other optical components is needed to enable precise guiding of the light beams. Research in this area is focused on the materials used, which must be extremely robust, especially if they come into contact with neutrons from the plasma chamber. Strong particle and radiation fluxes can damage the structure of the materials and lead to the formation of colour centres on the optics, which absorb some of the laser light and thus reduce the lens transmission. [40; 122; 17; 115] Another unresolved question in inertial confinement fusion concerns the **production of** large numbers of high-quality **targets**. None of the current facilities is yet capable of mass production, not least because research is still focused on the quest for the optimal target design. Consequently, production facilities are geared towards the flexible production of small batches rather than large, standardised batches. [17; 123; 90]

In both test reactors and potential future fusion power plants, **fuel** must be **delivered** to the inside of the plasma chamber frequently[24] and precisely enough to ensure a continuous fuel supply that maintains plasma stability. In principle, it could be delivered by gas guns or electrostatic/electromagnetic methods. Fuel delivery is easier in magnetic confinement fusion systems, because the frozen fuel pellets are fired directly into the plasma. In inertial confinement fusion, on the other hand, the shell containing the fuel in the indirect drive method and the fuel pellets in the direct drive method must be very precisely aligned, since the conditions required for fusion cannot be achieved without uniform X-ray irradiation or laser bombardment. Both methods also require the fuel pellets to have an exceptionally uniform surface, since compression and ignition could be impaired or prevented if the energy is not distributed symmetrically during the laser shot. [124; 17; 21; 25]

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[24] For the cited shot rate of 10 to 20 shots per second (10 to 20 hertz), an inertial confinement fusion power plant would need approximately 860,000 to 1.3 million targets a day [17].

Some existing **power plant technology** could be used to build a fusion power plant, for example the outer shell and the components that generate electricity and feed it into the grid (heat exchangers, steam generators, turbines, transformers). However, the components involved in the fusion process itself and in its control and monitoring will need to be developed from scratch to the point where they can be mass-produced. The development process should ideally bear in mind the (future) availability of the substances and materials used.[25] [125]

Operating a fusion power plant generates **neutron radiation**, although its intensity varies depending on the fuel mix employed. If the neutron radiation hits the plant's components, they are activated and become radioactive. Not least in the interests of personnel safety, the design, location and controllability of these components and any adjacent structures must allow for **remote maintenance** or automated replacement if required. The necessary solutions will also involve the development of suitable tools. Some initial experience has already been gained with test reactors such as JET. However, commercial operation would call for significantly shorter maintenance and replacement times [20; 126; 17] A modular design is thus key, even for some highly integrated components, since they would need to be replaced every 2 to 10 years throughout the planned power plant lifetime due to the high loads in the reactor core.[26]

6.3 Materials

The materials used, particularly those in the reactor core, must be extremely robust and reliable due to the high temperatures, pressures and/or levels of neutron radiation/X-rays. This applies equally to both magnetic and inertial confinement fusion. It is important for sensors and detectors, and especially for structural components that interact directly with the plasma or radiation, such as the first wall in the vacuum vessel, the blanket and the divertor.[27] [127] Divertors remove the reaction products and impurities from the core of magnetic confinement fusion reactors. This means that they come into direct contact with the outer edge of the plasma. Various approaches are being pursued to reduce the thermal load of components and on the reactor's first wall. These include the use of specific robust materials such as tungsten and special steels, as well as the cooling and stabilisation of the plasma edge (radiative cooling) and an optimised divertor shape that allows the energy load to be distributed over the greatest possible area. [20; 119; 17; 127; 100]

As well as damaging a material's surface, high temperatures, pressures and radiation loads can also alter its mechanical or thermal material properties and cause material fatigue. For example, neutron excitation or chemical processes can produce gases such as helium and hydrogen that can form bubbles and potentially cause material cracking, embrittlement or bulging. In addition, ablation processes can produce undesirable dust particles that impair the uniform distribution of the laser light in inertial confinement fusion or inhibit plasma ignition in magnetic confinement fusion.

Limited empirical knowledge poses a particular challenge for material development. It has hitherto not been possible to test most materials and components under their actual operating conditions. Some initial insights have been gained from computer simulations and material testing with particle accelerators or

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[25] Helium, for example, is currently only extracted in a handful of countries. It is mostly extracted from natural gas and is sometimes classified as a critical raw material, i.e. one with limited availability [108; 125]. As natural gas use declines due to the defossilisation of the energy system, supply sources could dwindle, making circular/recycling solutions increasingly important.

[26] Entler et al. give a figure of 4.5 to 10.5 years for components exposed to neutron radiation (for a power plant lifetime of 40 years) [126]. Häfner et al. suggest a frequency of every 3 to 5 years for the first wall and blanket [17]. Other experts estimate that the blanket would need to be changed every 5 years, while the divertor would have to be replaced every 2 years due to the particularly high loads it is exposed to (opinions expressed by IPP experts).

[27] The thermal loads on the reactor's first wall can briefly reach the megawatt per square metre range, with figures of up to 20 megawatts per square metre. This is double the load that the current technology is able to withstand. [20; 127; 17]

experiments in existing test reactors and in some cases also in nuclear fission power plants (when testing radiation resistance). However, structural changes in materials are difficult to simulate with computers, and test reactors cannot replicate the size of future power plant components. It is thus vital to develop powerful neutron sources that enable targeted testing of materials' suitability and durability in an environment exposed to high levels of neutron radiation. While there are some devices around the world that can produce neutrons with an energy of 14.1 megaelectron volts (MeV), they cannot do so with the neutron fluence required for material testing. The neutron fluence describes the intensity of the neutron field and thus the neutron load on the materials. In Europe, a powerful, high-energy neutron source is currently being built in Granada, Spain (IFMIF-DONES). It is scheduled to start operating in the mid-2030s and will contribute to the realisation of the DEMO test reactor. Moreover, a similarly powerful material testing neutron source (A-RNS) is being planned in Rokkasho (Japan), also as part of the DEMO research programme. [20; 17; 100; 128; 129; 130; 131]

6.4 Fuel

Most current fusion concepts use the hydrogen isotopes deuterium and tritium as fuel. However, although tritium has the advantage of good reactivity, there are also significant challenges with regard to its sourcing and the disposal of components that it has interacted with.

Unlike deuterium, which can be extracted from water and is thus available in sufficient quantities, only tiny amounts of radioactive tritium occur naturally.[28] Tritium is a beta emitter with a half-life of 12.3 years, and is mostly formed by the interaction of cosmic rays with nitrogen gas in the atmosphere, as well as in smaller amounts through interactions in lithium-bearing rocks. [128, p. 316] Global civilian reserves of tritium are estimated at just 30 to 40 kilograms, substantially less than the 56 kilogram annual tritium consumption of a 1 gigawatt (thermal) fusion power plant.[29] [132; 42] No technology capable of producing this amount of tritium currently exists. At present, CANDU-type heavy water reactors are the only significant civilian source. Tritium can be obtained as a by-product from the heavy water (D_2O) used as a moderator in these nuclear fission power plants. 30 to 35 reactors of this type existed worldwide in 2011, the majority in Canada (21). Together, they would have been able to produce a total of just 1.8 kilograms of tritium a year. [133]

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[28] The same is true of helium-3 (^3He), an alternative fusion fuel that is also very scarce in nature and is produced artificially from the decay of tritium. Boron, on the other hand, is more abundant. It is mainly mined in Chile, China, Russia and the USA. [128; 42]

[29] [132] estimates that the fuel burned by a fusion power plant with a thermal output of 1 gigawatt (GW_{th}) would come to approximately 56 kilograms of tritium and 37 kilograms of deuterium a year. [42] cites a figure of 170 kilograms of tritium for a 3 GW_{th} power plant, which is consistent with the estimate of 56 kilograms for a 1 GW_{th} power plant. Assuming the same ratio of fuels, a 3 GW_{th} power plant would require 111 kilograms of deuterium a year.

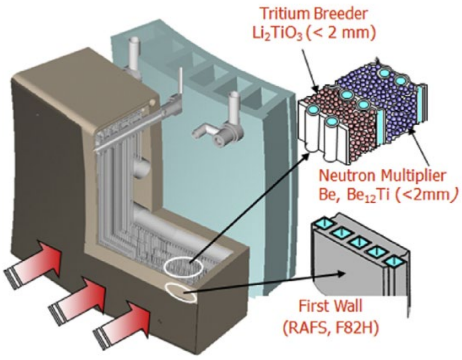

Figure 12: Section of a blanket wall concept illustrating the first wall, the tritium breeder and neutron multiplier, and the cooling system behind them: water-cooled concept using beryllium as a neutron multiplier; Source: Abdou et al. 2015, p. 6, CC BY-NC-ND 4.0 Deed [134]

In order to obtain the necessary quantities of tritium, researchers are investigating the production of tritium in the fusion chamber itself. This would potentially allow fusion power plants to produce their own tritium fuel. In the process known as tritium breeding, neutrons released from the plasma react with lithium[30] in the blanket behind the first wall (see Figure 12). Lithium and neutron multipliers are used to ensure that there are enough neutrons for breeding to take place. The preferred multiplier is beryllium, although lead is also an option. The tritium must be recovered from the resulting mix of substances and purified before it can be fed into the fuel cycle. The suitability and efficiency of various tritium breeding concepts currently under development will be tested for the first time in the ITER and DEMO test reactors. [135; 128; 42; 20]

Tritium breeding research and development has so far focused on blanket concepts for magnetic confinement fusion reactors. However, there are plans to also use the findings in inertial confinement fusion reactors, where tritium breeders will form part of an as yet undeveloped multifunctional blanket concept. [17] The situation for the alternative fuel helium-3 (^{3}He) is similar for both reactor types. Helium-3 is a decay product of tritium that also doesn't occur naturally on Earth in the necessary quantities. Like tritium, it would therefore need to be specially produced – in this case through fusion processes.

6.5 Waste management

The neutrons released in most nuclear fusion reactions create radioactive waste. The materials used in the reactor core determine how much radioactive waste is produced and whether or not it includes high-level waste. However, nuclear fusion will not generate large amounts of high-level radioactive waste – most or all of the waste will be low- to intermediate-level.[31] The storage and decay periods for the waste from fusion power plants would be significantly lower than for the high-level radioactive waste from nuclear fission power plants, which mainly consists of spent fuel rods [136]. Most studies estimate decay periods in the region of 100 years rather than the 100,000 years estimated for nuclear fission waste. [102; 17; 20] To achieve this, however, it will be necessary to use specific materials such as special steels that are harder to activate or don't form potentially long-lived radioactive isotopes. [20; 102]

Besides activated reactor components, tritium is the other main source of radioactivity in fusion power plants, since tritium deposits can form in some components. Decontamination of replaced components and decommissioned power plants would help to reduce the level of radioactive contamination. However, other

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[30] The stable lithium isotopes lithium-6 (^{6}Li) and lithium-7 (^{7}Li) are used for this purpose. Lithium-6 is currently preferred due to its better physical process properties and its higher affinity for producing tritium.

[31] In quantitative terms, these also account for most of the waste produced by nuclear fission power plants.

strategies should also be pursued, such as targeted material selection, reducing the time that spent fuel remains in the plasma chamber and recycling measures. The size of the contaminated power plant components means that fusion power plants would produce a larger overall quantity of radioactive waste than fission power plants.[32] [102; 17]

6.6 Regulation

The rollout and commercialisation of fusion power plants will call for a **stable regulatory framework**. This includes assigning responsibilities to the relevant regulatory and supervisory authorities and setting standards for the licensing and operation of nuclear fusion power plants. While Germany currently lacks a regulatory framework, there are initiatives to create one, for example in Canada, the USA, the United Kingdom, the EU (as part of the ITER project) and also at the International Atomic Energy Agency (IAEA). Although it is expected that most regulation will be at national level, efforts are also being made to promote voluntary, cooperative harmonisation of national regulations, as already happens with the IAEA processes for nuclear fission. [137]

There are strong calls from the fusion community to develop **specific regulations for fusion** rather than basing them on the regulations for nuclear fission. It is true that the two technologies have some things in common, such as the production of low-level and intermediate-level radioactive waste, the removal of large amounts of heat, and the need to limit internal and external discharges. However, there are also significant differences. These include the lack of fissile reaction products in nuclear fusion reactions, the passive safety associated with the physical principles of nuclear fusion, a different radioactive inventory and different critical material discharge paths. Taken together, these factors mean that the risk of incidents and the risks associated with accidents are lower. The hazard potential is thus lower than for nuclear fission (see also 1.2). The technical regulations should obviously be based on safety concepts for facilities with a radioactive inventory and should adopt a defence-in-depth strategy. The requirements specific to nuclear fusion include regulations for the use of tritium and standards for working with strong electromagnetic fields, cryogenic components and high-power lasers. [100; 137; 138; 17; 139]

In addition to developing operational safety regulations, it will also be necessary to regulate the **occupational health and safety and environmental aspects**. Radioactive tritium will be widely used in fusion plants, as well as various toxic substances such as beryllium and lead. These can be harmful to human health and/or the environment when working with them on a daily basis or in the event of an incident. Although radioactive, tritium itself is relatively harmless to humans and the environment. It is easily replaced by the commonest hydrogen isotope (^1H) in water and other substances. Moreover, the electrons emitted during its radioactive decay (beta radiation) contain relatively little energy. Tritiated water (10 days) and organically bound tritium (40 days) both have a short biological half-life, a measure of how quickly a radionuclide is eliminated from the body. Consequently, tritium is only harmful to human health if it enters the body in large amounts.[33] [137; 140; 103; 141; 142; 103]

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[32] For instance, the planned DEMO research reactor may produce approximately 10,000 tonnes of waste from in-vessel components. This is roughly four times as much as the Generation IV European sodium-cooled fast reactor (ESFR) that is currently under development, where the equivalent figure is in the region of 2,500 tonnes. [102]

[33] The World Health Organization (WHO) drinking water quality standard for tritium is 10,000 becquerels per litre. If you drank two litres of water with this concentration of tritium every day for a year, you would be exposed to a radiation dose of 0.1 millisieverts (mSv) [141]. To put this in context, the average exposure to natural radiation sources in Germany is 2.1 mSv a year [142]. For the ITER test reactor, the radiation dose criterion for evacuation was set at 50 mSv. This dose was not reached in a simulation of different accident scenarios for various tokamak power plant types – in fact, the doses in all the simulated scenarios were far below this intervention dose. [103]

In view of the limited empirical knowledge currently available, an **iterative approach** should be taken to the **regulatory framework**'s development in order to reflect the state of the art in fusion research and enable any necessary regulatory amendments. The technology's development is covered by existing national and international regulations, norms and safety standards that must be followed by design engineers, research facility operators, supervisory authorities, etc. Consequently, regulations that can be built on already exist for many processes. For instance, there are already regulations, know-how and qualified personnel in the power plant and plant engineering sectors and general regulations for working with lasers, high pressures, radioactivity and hazardous materials. One benefit of the fact that fusion power plants are still in the early stages of development and won't be realised for many years to come is that regulatory questions can be addressed in the design of components, materials and power plant facilities. This applies to questions such as occupational health and safety, the reduction of radioactive waste and recycling. Measures such as limiting the amount of critical materials, remote maintenance and monitoring and the incorporation of extra safeguards can enhance operational safety and reduce environmental and proliferation risks. [34] [100; 137; 17]

The **proliferation risks** for fusion power plants are lower than for nuclear fission reactors. The main risks associated with nuclear fusion concern the supply of tritium, which is also used in nuclear weapons, and the targeted use of the neutrons produced in fusion reactions. Tritium is used with deuterium as a fuel in hydrogen bombs, and is also employed to increase the yield of boosted fission weapons. Another proliferation-related concern is that the neutron bombardment in a fusion power plant can theoretically turn fissile material into weapons-usable material (e.g. ^{238}uranium into ^{239}plutonium or ^{232}thorium into ^{233}uranium) that could then be used as fuel for nuclear weapons. However, the amount of fissile, weapons-usable material that could be obtained in this way would be relatively small compared to certain types of nuclear fission power plant. Furthermore, if inspection agencies like the IAEA were granted access to the facilities, they could employ various detection methods to discover any misuse of fusion power plants. In order to reduce the proliferation risks associated with fusion power plants, potential misuses should be addressed in their design and appropriate countermeasures developed and implemented. Possible approaches include recording the background radiation near coolant loops, integrated devices/processes for assaying incoming materials, and qualitative or quantitative assessment of the reaction products. In order to enable more accurate assessment of the risks and develop targeted countermeasures, it would also be useful to carry out more detailed engineering assessments of the time required to replace blanket modules (which can bring fissile material into the reactor) and the time needed to restart a fusion power plant if the modules are replaced illicitly. A better understanding of techniques for extracting plutonium or uranium from the blanket cooling system could also help to mitigate proliferation risks. Additionally, critical components could be declared to be dual-use goods, making them subject to export controls. However, this would hinder the technology's commercial rollout. [143; 144; 145; 17]

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[34] Proliferation is the spread or transfer of weapons of mass destruction or associated technologies and components. As a rule, the aim is to prevent or at least limit proliferation.

7 The timeframe for building a fusion plant

Researchers have been investigating the production of energy from nuclear fusion since the 1950s [146]. Yet while several research reactors now exist, there are still no fusion power plants. Although not impossible, it is unlikely that the first plant will be built in the next two decades. There is a consensus among many experts that the first fusion power plant could start supplying electricity to the grid in 20 to 25 years' time. There are those, especially in the startup community, who believe that it can be done in a much shorter timeframe of around 10 to 15 years. However, the majority regard this as unrealistic, not least because the construction of a power plant alone would take several years. Opinions differ as to whether the forecast timeframes relate to the construction of a demonstration power plant or the first commercial (first-of-a-kind) power plant. [88; 115; 155; 71]

When assessing these forecasts,[35] it is important to bear in mind that ambitious timeframes could be affected by competition for financial resources and/or public attention. [147; 148; 149] Furthermore, the estimates about when the first fusion power plant could commence regular operation are subject to a great deal of uncertainty. This is due to the complexity of the technology, the fact that many of the technological solutions for reactor components, materials, cooling systems, fuels and safety systems have yet to be developed (see Chapter 6), and the current lack of comparator/model facilities to provide empirical operating knowledge. In view of these uncertainties, it may still be several decades before a working nuclear fusion plant is built, and it is even possible that that the breakthrough will never be made at all.

On the other hand, there are a number of factors that support the view that a fusion power plant could start supplying power to the grid within the next 20 to 25 years. There have been numerous scientific advances in recent years, for example in power removal for tokamaks, the achievement of laser fusion ignition with energy gain at the NIF in December 2022, and the JET tokamak's energy record set in October 2023. There have also been several parallel development activities at research institutions, while the number of startups in this field continues to grow, fuelling competition. A further positive factor is the significant increase in private investment and public funding (see Chapters 4.2 and 9). [115; 70; 21; 17]

Fusion power plants in the currently envisaged 1-2 gigawatt range (see Chapter 5) would fall into the large power plant category. Not least in the energy sector, projects on this scale tend to suffer from construction delays and cost overruns (see also Chapter 8) that can sometimes be significant. [150[36]; 151] In addition to construction delays, another factor that future time and cost planning should take into account is that, in the past, nuclear fusion research has tended to be over-optimistic about the timeframes for achieving the necessary technological advances and for building the relevant facilities. [42; 101] Growing competition for research capacity and funding due to the rising number of actors in this field could perpetuate this trend. While over-optimistic estimates could increase the likelihood of delays, it is also possible that greater competition could result in projects being implemented sooner.

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[35] In this context, it is also important to bear in mind that any assessment of the prospects of realising a plant and of the implementation timeframes, cost estimates, etc. is complicated by the fact that studies, papers and articles about nuclear fusion can suffer from a structural bias with regard to the potential for the technology's implementation. Most actors with the necessary technical expertise and relevant research knowledge to properly assess the status quo and development prospects of nuclear fusion and its different technology concepts work in this field themselves or are directly or indirectly involved in nuclear fusion projects. (see also [101; 147] It is known that experts engaged in technology foresight are in general subject to biases such as positive framing (where they focus on the technology's positive implications) or the desirability bias (where they overestimate the likelihood of positive development conditions). [148] The reasons for these biases are psychological [149] (Tversky & Kahnemann 1981). Consequently, any evaluation of these forecasts should be especially sensitive to the fact that the parameters, assessments, etc. that underpin them are not only subject to uncertainties but can also – whether consciously or unconsciously – be cast in an overly positive light. Moreover, nuclear fusion is a highly complex technology that is still the subject of basic research. Structural reasons mean that, unlike established technologies, it cannot be critically assessed on the basis of the experience gained from day-to-day plant operation, while the general public lacks the technical knowledge to make informed judgements.

[36] In this case, publicly funded projects.

Many experts believe that it will be challenging to build the first fusion power plant that supplies energy to the grid within the next 20 to 25 years. They stress that doing so will require close coordination of all the individual aspects that need to be addressed and goal-oriented collaboration between the relevant stakeholders. This will also entail accelerating and coordinating development processes and carrying them out in parallel.[37] [152] For example, the time taken for a reactor core material to get from the early development stage to the point where it is approved for use in operating conditions, including nuclear licensing, has typically been around 30 years. [100] An ambitious, incremental and iterative development process must therefore be applied to partly competing concepts, with parallel research being carried out into individual technological solutions and scaling occurring in successive sub-steps.

In addition to project-related aspects, the overall conditions will be key to determining the prospects of successful commercialisation within the envisaged timeframe. These include the ability to raise the necessary financial resources, the development of a stable but adaptable regulatory system and the formulation of legally and socially acceptable safety concepts (see Chapters 6 5 and 8). In order to meet the future need for specialist personnel, fusion experts are calling for the development of specific curricula for this field, as well as the establishment and funding of research clusters, junior research groups and formats facilitating the exchange of ideas between academics and engineers from different countries. In addition to scientists, as the focus of development activities shifts from basic to applied research and implementation, there will be a growing need for engineers, planners and potential power plant operators. [17; 21; 88; 71] The development and establishment of the relevant programmes and curricula – which will take place in a social as well as a regulatory context – will require time and other resources. This should be taken into account when formulating ambitious schedules for building the first fusion power plant.

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[37] The ITER test reactor has received some criticism in this regard. The reactor's construction is the world's largest and most expensive fusion project to date ([26] puts its cost at 18 to 22 billion euros). It was originally scheduled to start operating in 2016, but the date has since been pushed back several times, first to 2025, then to 2035, and now to 2039 for the deuterium-tritium operation phase. [26; 152; 98; 61] Apart from the various technical problems, another factor is that ITER is an international research collaboration that is to some extent affected by the political interests of the participating nations. Together with its special funding arrangements, these political factors have also caused delays in its development and construction, not to mention logistical challenges. For reasons that include enabling added value for as many partners as possible, the reactor's individual components are being developed and produced in different countries and must then be transported to France. This means that ITER is not directly comparable to a commercial project. Nevertheless, the planning and construction of the test reactor are highlighting challenges that can provide valuable empirical knowledge for the realisation of the first power plant. [26; 152]

8 Potential integration with the energy system

The 20 to 25-year implementation timeframe regarded as feasible by the experts means that nuclear fusion will be unable to make a meaningful contribution to meeting the 2045 climate targets in Germany or the 2050 targets in Europe. And even if it is successfully rolled out, it will encounter an energy system largely characterised by renewable energy, decentralised supply structures and imports of synthetic hydrocarbons and other hydrogen derivatives. Nuclear fusion will have to show that it can compete in this remodelled system. That said, the projected rise in global electricity demand [153; 106] could present an opportunity for operational fusion power plants in the second half of the century, for example in key industrial regions.

8.1 The key role of electricity production costs

When assessing whether the use of nuclear fusion in the future energy system would be economically advantageous, it is not enough to only consider the levelised cost of electricity (LCOE). While this plant-based metric describes the cost at which fusion power plants could supply electricity to the grid, it is the **whole-system cost** that is key to a secure energy supply. As well as the levelised cost of electricity, this includes the cost of power storage systems, grids and consumption systems. A study by the Academies' Project "ESYS" looked at the whole-system cost of various technologies, including nuclear fusion. It found that the use of fusion power plants only makes sense from a whole-system perspective if their cost falls below a certain threshold, the exact level of which is determined by a variety of factors. An operational power plant would need to be able to supply electricity at a little under 10,000 euros per kilowatt of net electrical output. [154]

At present, the cost of electricity from fusion power plants and thus the feasibility of commercial operation cannot be predicted with any confidence. [155; 42; 101] Among other things, this is due to the **uncertainty** about whether it will be possible to commercialise the technology, which power plant concepts will ultimately make it to the application stage, the length of time before a power plant is built and how the cost of other net-zero energy technologies will evolve between now and then. In view of the long projected realisation timeframe, it will be important to keep a close eye on the future development of competing climate-friendly and net-zero technologies such as solar PV and power storage technologies, since this will affect the economic prospects of fusion power plants. Lastly, geopolitical developments can also affect the cost structure to a greater or lesser degree, or at least influence the context of the technology's development. It is impossible to predict how widely knowledge and research strategies will be shared internationally over the next few decades, how political tensions, crises and wars will affect the energy industry, or the extent to which the energy transition and climate change will be regarded and treated as important policy issues and endowed with the necessary resources and infrastructure.

Despite all these uncertainties, initial **estimates of the levelised cost of electricity** of future fusion power plants provide a rough idea of what might be expected. An overview of different fusion power plant reactor designs puts the range of LCOEs at between 40 and 165 dollars per megawatt hour, approximately equivalent to 38–157 euros[38] per megawatt hour.[39] [156; 157] It is not possible to say for sure whether the

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[38] Based on the 2022 exchange rate of 1 dollar = 0.9509 euros [156].

[39] The LCOE range cited in Griffiths et al. is supported by other studies, although they give a somewhat higher level for the lower value in the range. [126] calculates a range of 75–160 dollars per megawatt hour ($/MWh) (= 64–136 €/MWh at the 2018 exchange rate of 1 US dollar = 0.8473 euros – see [156]). In this study, the LCOE given for fossil energy is somewhat lower and the LCOE for renewables somewhat higher than in Griffiths et al.. However, some of the reference data for electricity production in Entler et al. significantly contradicts the 2030 and 2050 IEA forecasts for the LCOE of renewable energy and nuclear fission (see [153, e.g. the table on p. 201]). The IEA figure for nuclear power is higher than the figure cited in Entler et al. 2018, whereas the figure for renewables is at the lower end of the range in Griffiths et al.. Both thus

lower LCOE figures in this cost range are achievable. Nuclear fusion is fundamentally a new technology, and there are thus various risk factors that suggest the figure is likelier to be somewhere between the middle and upper end of the range. A handful of fusion plants lacking operating experience would initially be competing against established electricity production methods. It is therefore likely that, at least to start with, the LCOE would be towards the upper end of the range.[40] Moreover, a fusion power plant in the most widely envisioned 1-2 gigawatt range would be classed as a large power plant and its construction would therefore be a large-scale project. In their cross-sectoral study, Kostka and Anzinger show that the cost overruns for large-scale public energy projects are among the highest for the whole of German industry, and that the risk of spiralling costs is especially great for pioneering projects.[41] [150] Significant cost overruns and/or high entry costs would mean that the first fusion power plants would probably be reliant on government subsidies, grants or purchase guarantees in order to enter the market. There is nothing unusual about this, provided that the technology promises to become commercially viable once more experience with it has been accumulated and economies of scale are achieved. However, the costs associated with its introduction should be shared as widely as possible among the technology's different potential users. The extent to which learning effects, structurally simpler reactor designs and targeted waste heat utilisation contribute to cost degression remains to be seen.

8.2 Potential areas of application

The high investment costs and relatively low operating and fuel costs mean that fusion power plants would need to be run on high full-load hours to cover their costs. In this respect, they differ from gas-fired power plants, for example, where fuel accounts for a significant percentage of the total costs. Fusion power plant operation would thus be **similar to today's base load power plants**. [158; 70]

In addition to covering the energy demand of densely populated regions and energy-intensive industrial locations, other potential **areas of application** for fusion power plants include seawater desalination, direct air capture of carbon dioxide (DAC) and electrolytic hydrogen production. [101] Their ability to deliver a continuous energy supply and integrated waste heat utilisation make fusion plants a promising option for desalination and DAC. As far as hydrogen production is concerned, it currently appears likely that, in places where enough renewable electricity is available, hydrogen electrolysis powered by renewables would be more cost-effective, even though electrolyser capacity utilisation would be lower.[42] [159] However, using energy from fusion power plants could help to increase hydrogen production in Germany, reducing the percentage of imports. [154]

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support the conclusions of Griffiths et al.. [157] concludes that the LCOE for nuclear fusion will need to be 80–100 $/MWh (= 74–92 €/MWh at the 2023 exchange rate of $1 = €0.9248 – see [156]), although the figure for early fusion designs will more likely be in the region of 150 $/MWh (= 139 €/MWh).

[40] For example, [126] models an LCOE of approximately 160 $/MWh (= 136€/MWh at the 2018 exchange rate of $1 = €0.8473 – see [156]) for a demonstration power plant. This is much higher than the market price and would thus not be competitive without financial support.

[41] 10 of the 170 projects in this cross-sectoral study are energy projects. The authors propose several general explanations for the identified cost overruns. These include the interface complexity of large-scale projects, (technological) challenges that could not be foreseen at the start of the project, over-optimistic project planning and inadequate governance models for first-of-a-kind technology implementations. The last of these issues can lead to a lack of clarity regarding responsibilities and risk-sharing, and the creation of false incentives for businesses. [150]

[42] The levelised cost of producing hydrogen with an electrolyser at 500 euros per kilowatt of electric capacity (€/kW$_e$) and electricity at 4 cents per kilowatt hour (ct/kWh) over 2,000 hours a year is the same as with electricity at 6 ct/kWh over 7,500 hours a year. Handley et al. recognise that the use of electricity from fusion power plants for electrolytic hydrogen production will not be cost-competitive in locations where there is an adequate supply of renewable electricity [159].

8.3 Integration with a renewables-based energy system

Renewable energy installations generally have a shorter life cycle than large power plants (20 to 30 years as opposed to 40 to 60 years) and are built continuously over time. This means that, at any point in time, there are always some renewable installations that need replacing, providing **producers** with the opportunity to **integrate** new, competitive technologies. By the time nuclear fusion is expected to enter the market around the middle of this century, the energy sector's transmission and distribution networks and storage and import infrastructures will have been restructured and rebuilt. The new structures will be geared towards a growing proportion of renewable energy and will thus be smaller-scale. This could potentially complicate or hinder the integration of a new large power plant type.

As long as the system has enough internal **flexibility**, large power plants can still be cost-effectively integrated with an energy system dominated by intermittent energy production. [154] In addition to power storage systems and the hydrogen system, the necessary electricity system flexibility can be enabled by greater use of digital technology for faster and more efficient data processing, targeted management of private, industrial and service-related consumption patterns, and an even more interconnected European power grid covering a wider geographical area. The integration of fusion power plants could reduce the frequency of times when demand exceeds supply, since they would increase the overall supply of electricity and deliver a constant supply, making them especially important at times when high demand coincides with low supply from other production sources. [158; 154]

Fusion power plants could compete with nuclear fission power plants in countries that still rely on **large power plants** and especially nuclear power. Fusion power plants could gradually replace existing fission power plants due to the much lower radiation risk in the event of an accident, the shorter radioactive waste decay times and the prospect of correspondingly greater public acceptance. There would be few barriers to the integration of fusion power plants in these countries. Another advantage over nuclear fission is that, in the current concepts, some of the fuel used in fusion power plants could be produced on site rather than being imported and would be available on a long-term basis. Some studies also argue that nuclear fusion could be a valuable option in countries that have limited space for renewable energy installations. [160; 161]

As a complex, capital-intensive technology, the experts do not expect nuclear fusion to be immediately rolled out in several countries as soon as it becomes commercially viable. Instead, they consider it likely that most of the early adopters will be countries that currently dominate nuclear fission technology and can draw on their experience of using this advanced technology and working with radioactive materials. Accordingly, the use of nuclear fusion would initially be concentrated in economically strong industrialised and newly industrialised countries such as the USA, France, China and India. It would only spread to other newly industrialised countries and perhaps also developing countries as a second- or third-generation technology, assuming that the high investment costs of the first-generation power plants can be significantly reduced. [161; 101]

9 Summary and outlook

The rollout of nuclear fusion would provide a low-emission source of electricity that could reduce German and European industry's reliance on energy imports and strengthen their competitiveness. However, it is not currently possible to confidently predict whether and by when it will become commercially viable. Nuclear fusion's role in the future energy system will largely be determined by the cost of the electricity supplied by fusion power plants. Based on what we know today, fusion power plants would be commercially viable if they were able to achieve costs in the lower range of current LCOE forecasts, provided that the alternative net-zero power generation and storage technologies do not experience any significant cost degression before fusion power plants enter the market. If nuclear fusion becomes established as a new technology, fusion technology companies and suppliers could use their position as technology leaders to unlock new global markets. Other economic benefits may arise even sooner, for example through spin-offs, alternative applications and patents resulting from fusion research and development.

Against this backdrop, there is good reason to press ahead with nuclear fusion research, albeit without delaying the transformation of the energy system needed to achieve net zero in Germany by 2045 and the rest of Europe by 2050. In other words, the pursuit of nuclear fusion should complement rather than hold back other efforts to achieve a net-zero energy system. The active, targeted expansion of existing net-zero technologies must continue if Germany and Europe's statutory commitments to achieving net-zero greenhouse gas emissions are to be met.

According to the experts, it will only be possible to build the first fusion power plant that supplies energy to the grid within the next 20 to 25 years if government and the private sector fully commit to taking all the necessary steps in parallel and in a coordinated manner. This applies to both the technological challenges – including the ongoing development of reactor components, the development of robust materials and the closing of the fuel cycle – and the overall conditions such as the regulatory framework, technical regulations, appropriate financial instruments and the training and retention of the necessary specialist personnel. Establishing the regulatory principles as early and proactively as possible can help to mobilise domestic and international private capital by reducing investment risks. This is just one of the reasons why the debate about nuclear fusion must no longer be confined to the experts – it is essential to engage the wider public. People from all sectors of society should be transparently informed about the opportunities and risks of nuclear fusion, so that they too can actively engage in the future development processes.

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Authors

Sven Wurbs (ESYS Project Office | acatech), Sonja Dehlwes (ESYS Project Office | acatech), Dr. Andrea Lübke (acatech), Dr. Cyril Stephanos (ESYS Project Office | acatech), Philipp Stöcker (ESYS Project Office | acatech), Prof. Dr.-Ing. Manfred Fischedick (Wuppertal Institute for Climate, Environment and Energy), Prof. Dr. Hans-Martin Henning (Fraunhofer Institute for Solar Energy Systems ISE), Prof. Dr. Andreas Löschel (Ruhr University Bochum), Prof. Dr. Ellen Matthies (Otto von Guericke University Magdeburg), Prof. Dr. Karen Pittel (ifo Institute), Prof. Dr. Jürgen Renn (Max Planck Institute for the History of Science), Prof. Dr. Dirk Uwe Sauer (RWTH Aachen University), Prof. Dr. Indra Spiecker genannt Döhmann (Goethe University Frankfurt)

Additional contributors

Prof. Dr. Tony Donné (Frontiers in Energy Innovations – FEInn), Felix Fischer (ESYS Project Office | acatech), Prof. Dr. Dr. h.c. Siegfried H. Glenzer (SLAC National Accelerator Laboratory (Stanford University)), Prof. Dr. Sibylle Günter (Max Planck IPP/EUROfusion), Prof. Dr. Constantin Häfner (RWTH Aachen University | Fraunhofer Institute for Laser Technology| Fraunhofer Society), Dr. Alexander von Müller (Max Planck IPP), Polina Pienkina (ESYS Project Office | acatech), Prof. Dr. Markus Roth (Focused Energy | Technical University of Darmstadt)

Editorial office

Claire Stark (ESYS Project Office | acatech)

Graphics production

Annika Eßmann (ESYS Project Office | acatech)

Coordination of production and typesetting

Annika Seiler (ESYS Project Office | acatech)

Grafik design

aweberdesign.de

Series editor

acatech – National Academy of Science and Engineering (lead institution)
Munich Project Office, Karolinenplatz 4, 80333 Munich | www.acatech.de

German National Academy of Sciences Leopoldina
Jägerberg 1, 06108 Halle (Saale) | www.leopoldina.org

Union of the German Academies of Sciences and Humanities
Geschwister-Scholl-Straße 2, 55131 Mainz | www.akademienunion.de

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Contact:

Dr. Cyril Stephanos
Head of Project Office "Energy Systems of the Future"
Georgenstraße 25, 10117 Berlin
phone: +49 30 206 30 96 - 0
e-mail: stephanos@acatech.de
web: energiesysteme-zukunft.de/en

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German National Academy of Sciences Leopoldina
Jägerberg 1
06108 Halle (Saale)
phone: +49 (0) 345 47239-600
fax: +49 (0)345 47239-919
e-mail: leopoldina@leopoldina.org

Berlin Office:
Reinhardtstraße 14
10117 Berlin

acatech – National Academy of Science and Engineering
Karolinenplatz 4
80333 München
phone: +49 (0) 89 520309-0
fax: +49 (0) 89 520309-9
e-mail: info@acatech.de

Berlin Office:
Georgenstraße 25
10117 Berlin

Union of the German Academies of Sciences and Humanities
Geschwister-Scholl-Straße 2
55131 Mainz
phone: +49 (0) 6131 218528-10
fax: +49 (0) 6131 218528-11
e-mail: info@akademienunion.de

Berlin Office:
Jägerstraße 22/23
10117 Berlin