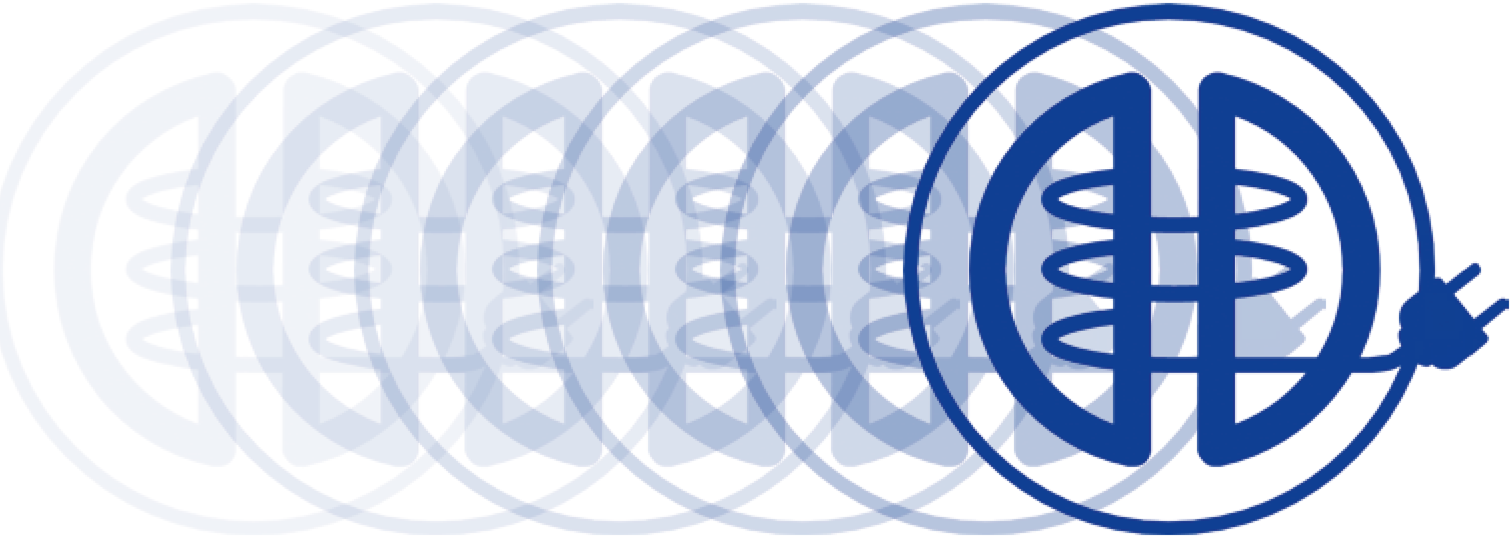
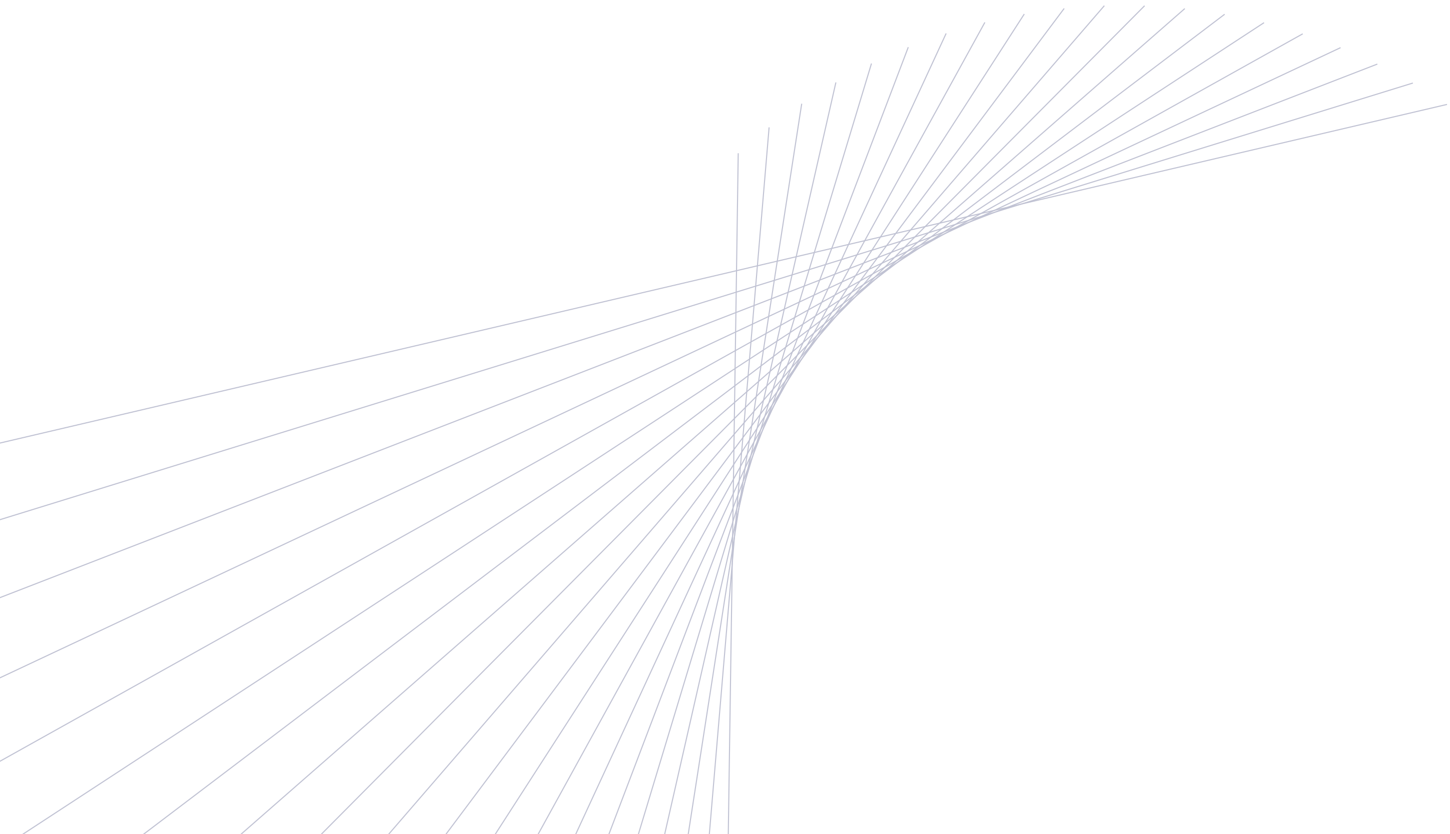
Source: https://www.euro-fusion.org/eurofusion/roadmap/
"ROADMAP IN BRIEF"
https://www.euro-fusion.org/fileadmin/user_upload/EUROfusion/Documents/TopLevelRoadmap.pdf
See pages 3, 6, 15

IN BRIEF

European Research Roadmap to the Realisation of Fusion Energy



EUROfusion



The European Fusion Roadmap outlines the research and development required to provide the basis for an electricity-generating fusion power plant.

In the short to medium term, the key research infrastructure is the ITER project, a worldwide endeavour, which will demonstrate the scientific and technological feasibility of fusion on Earth.

ITER will generate ten times more fusion power than the power injected to sustain the fusion process. While the design of a demonstration fusion power plant DEMO is already on-going, high-performance operation of ITER will give important input to fine-tune the DEMO design. DEMO will demonstrate first electricity production to the grid by fusion.

Combating climate change

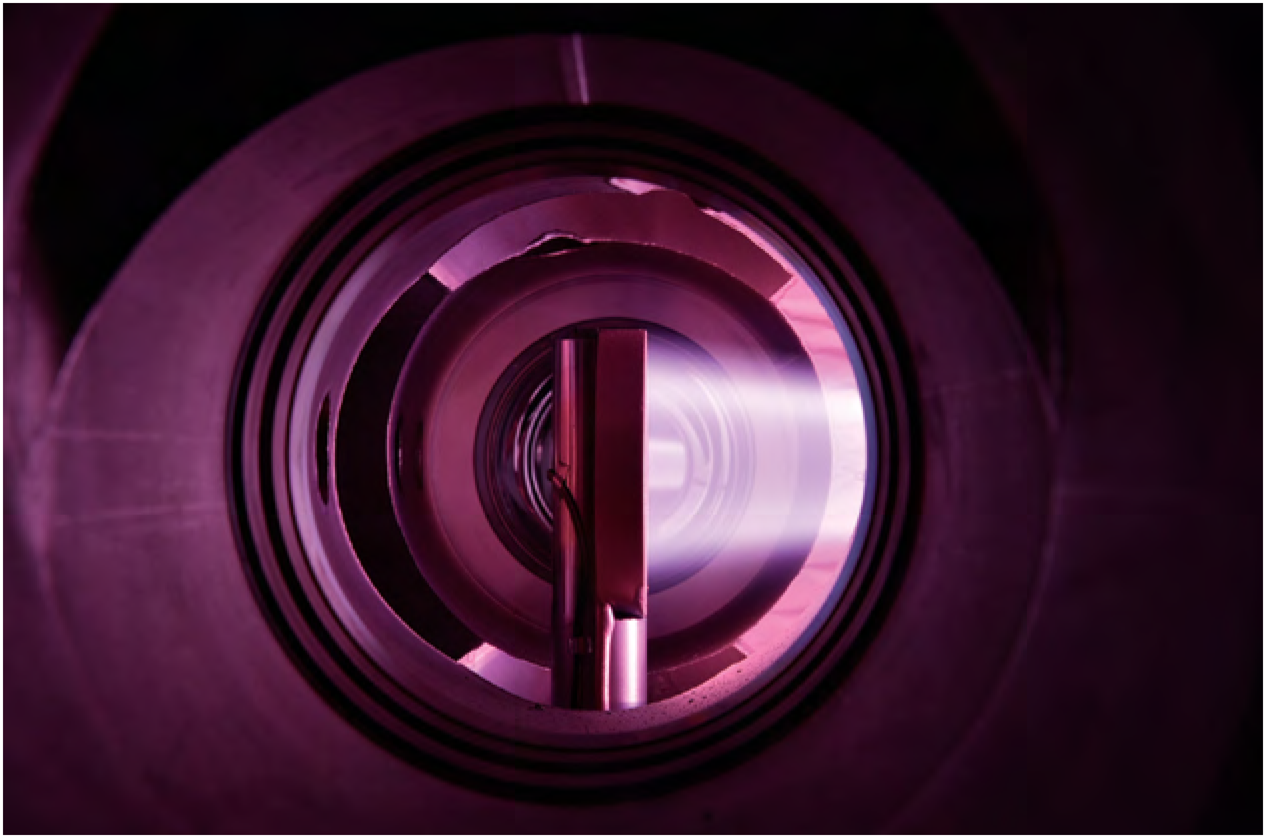
Worldwide, many countries are investing in fusion research and development, driven by an ever-rising energy demand of a growing population as well as by growing GDPs in developing countries. Ensuring competitiveness and securing our energy supplies is of prime concern but is only sustainable when combined with combating climate change. Energy sources that are carbon-free and sustainable are therefore crucial for our future prosperity and well-being. For the European Union, achieving clean energy is a high priority. Efforts towards this goal are spearheaded by the Energy Union strategy.[1] It recognises fusion energy as a potential long-term solution and understands that Europe needs to remain at the forefront of developing fusion technologies.

In Europe, the road to fusion energy focusses on using magnetically confined plasmas at temperatures above 100 million degrees Celsius and with long enough duration for commercial use. Although, in laboratory settings, hot plasmas at these temperatures are routinely confined by strong magnetic fields, challenges remain in creating the right conditions for generating fusion energy on Earth.

Fusion is the most extensively studied idea for a low-carbon primary energy source; it can be a new source that can deliver base-load electricity and complement intermittent low-carbon energy sources that are already being exploited.

Fusion on Earth

Fusion is the merging of two light atoms to form products with a total mass that is less than that of the original atoms. The mass difference is converted into energy according to Einstein's famous formula. The fusion reaction that is easiest to exploit is between the hydrogen isotopes, deuterium and tritium, with the reaction products being helium nuclei and neutrons.

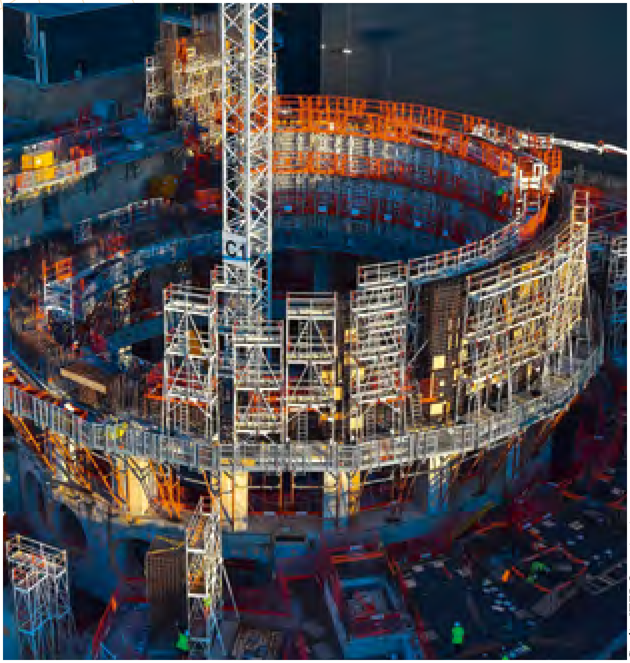


Credit: EUROfusion

Plasma is a superheated gas where electrons are no longer all bound to atomic nuclei, i.e., positively charged ions and negatively charged electrons move around freely.

ITER

Proving feasibility



Credit: ITER Organization

Magnetic confinement fusion has demonstrated that energy can be produced. Now its feasibility at a scale approaching a power plant will be proven. This is the purpose of ITER,[2] the world's largest experimental fusion facility, sited in the south of France as part of a worldwide collaboration. ITER will not generate electricity, but will be an important step towards electricity production from the demonstration fusion power plant: DEMO.[3]

A strong programme of accompanying research and innovation is needed alongside ITER and DEMO. An essential element in this respect is the realisation of a test facility, called IFMIF-DONES, for validating materials to be used in the harsh conditions of a fusion power plant.

The Joint Undertaking Fusion for Energy was established with an initial 35-year mandate, to deliver Europe's majority contribution to ITER, to contribute to the Broader Approach[4] and to work on the long-term objectives of the European fusion programme. All ITER parties have their own domestic agencies for their contributions.

The benefits of fusion power

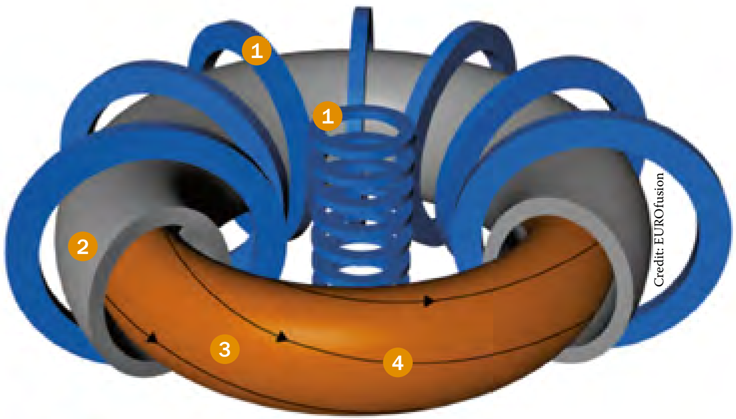
The fusion fuel is abundant. Tritium can be produced from lithium, a metal ubiquitous in the Earth's crust and in seawater. There is also enough deuterium dissolved in natural water to fuel fusion power plants for tens of thousands of years without risk of shortages or monopoly of supply.

The fusion power plant is inherently safe: less than a gramme of fuel makes up the plasma, which rapidly extinguishes itself in case of any malfunction. Deuterium-tritium reactions release neutrons which will activate wall materials. The resulting radioactive by-products are short-lived and decay in a period of about 100 years, to a level comparable to that of the waste from coal power plants. The benefits of fusion power as a carbon-free, sustainable energy source to complement renewables are persuasive arguments in favour of fusion.

RESEARCH

A concerted programme

In parallel to ITER construction, a vigorous Research & Development programme complements the activities of Fusion for Energy. This comprises, amongst others, research in support of future ITER operation and preparation for DEMO. Both are coordinated by EUROfusion,[5] the European Consortium for the Development of Fusion Energy, which is co-funded by Euratom and its participating nations.
All European fusion research laboratories contribute with their individual expertise.



A brief history of fusion

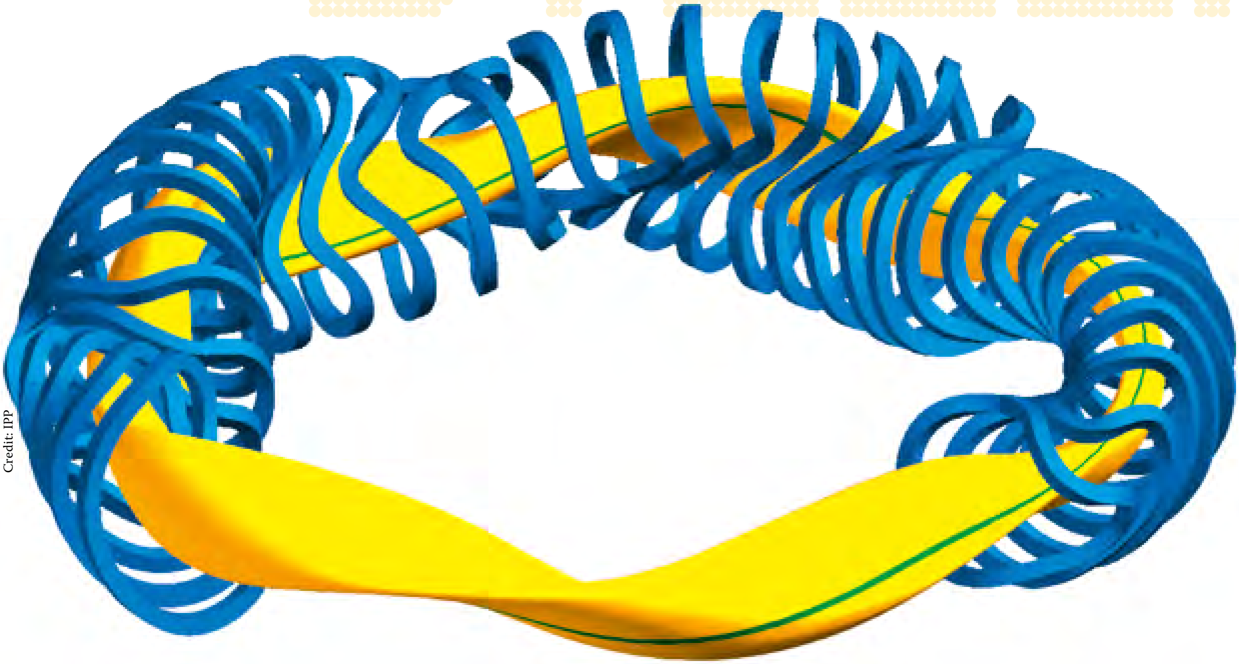
1 Coils
2 Vessel
3 Plasma
4 Magnetic field line

The breakthrough into the peaceful use of fusion as an energy source began in Russia in 1968 when a magnetic confinement device was tested with a hitherto unseen capacity for containing high-temperature plasmas. The new concept was called tokamak and has been the focus of Research & Development ever since.

The success of the tokamak prompted the construction of larger devices that started operation in the first half of the 1980s, such as the Joint European Torus (JET) in Culham, UK, the Tokamak Fusion Test Reactor (TFTR) in Princeton, USA and the Japanese Tokamak (JT-60) in Naka, Japan. Many complementary devices and facilities around the world were also built to investigate the broad range of science, technology and engineering challenges.

International plans were drawn up for a next step device approaching the power plant scale. An important milestone was achieved in the 1990s when JET and TFTR generated fusion energy using a mixture of tritium and deuterium. On this basis, Europe developed a first coherent, comprehensive goal-driven programme for addressing the challenges of a fusion power plant based on the tokamak concept.

STELLA



Credit: IPP

Artist's view of the Wendelstein 7-X stellarator. The stellarator has a number of advantages over a tokamak but is more complex to build and therefore not at the same development stage as the tokamak.

A sound basis for a long-term programme

Achieving commercially viable fusion requires a substantial amount of coordinated resources deployed at a European level over a long period of time. In order to structure the required effort, a roadmap to fusion energy was developed and agreed upon by the fusion stakeholders. This roadmap forms the basis for the programmes of EUROfusion and Fusion for Energy. It provides a clear and structured way forward to commercial electricity from fusion.[6] The rate of progress depends on various critical technical milestones and on the resources available.

The roadmap also emphasises the essential role that industry must play. To ease the involvement of industry, Fusion for Energy has published a policy paper[7] giving its industrial vision for ITER construction and preparation for DEMO. EUROfusion already actively involves European industry in the early phases of the DEMO design. The Fusion Industry Innovation Forum assists both Fusion for Energy and EUROfusion in involving European industry.

The roadmap to fusion electricity rests on three main pillars: ITER, DEMO and a fusion materials testing facility (IFMIF-DONES). Key aspects of these facilities are expanded upon later in the document. As part of its innovation and backup strategy, the roadmap includes a possible long-term alternative to tokamaks: the stellarator – a concept that confines plasma differently with potential advantages to be exploited. The fusion community regards Wendelstein 7-X as Europe's flagship device[8] which is well integrated in the overall research line, as it gives important additional input to ITER and DEMO.

THREE

The road to fusion electricity

Three stages to design fusion power plants

Near term

- Construction of ITER
- Research & Development in support of ITER
- Deuterium-tritium operation of JET
- Concept Design phase of DEMO
- Research & Development for DEMO
- Construction of a fusion materials testing facility, IFMIF-DONES
- Scientific and technological exploitation of the stellarator concept

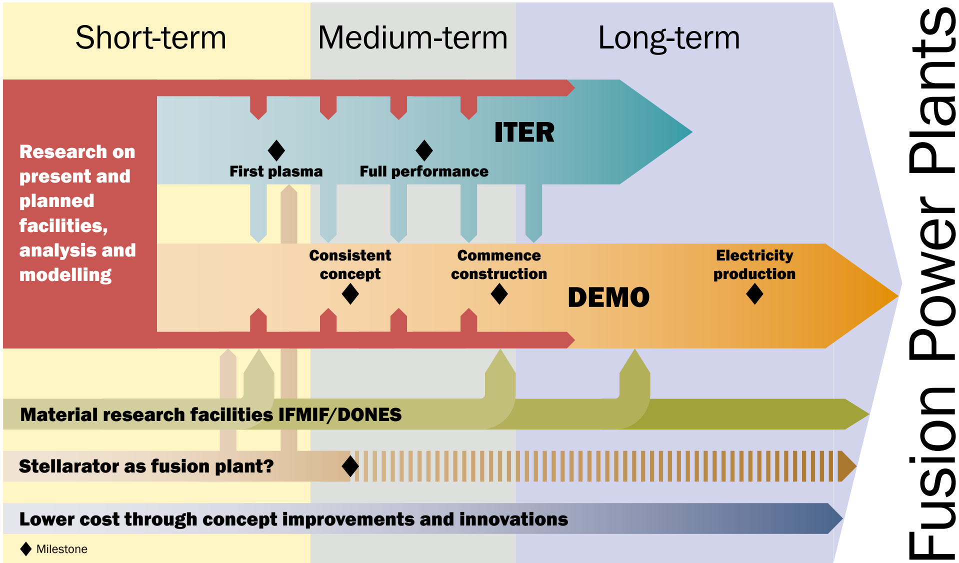
Medium term

- First scientific and technological exploitation of ITER
- First exploitation of IFMIF-DONES
- Engineering Design phase of DEMO with industrial involvement
- Development of power plant materials and technologies
- Possible further development of the stellarator concept

Long term

- High performance and advanced technology results from ITER
- Qualify long-life materials for DEMO and power plants with IFMIF-DONES
- Finalisation of the design of DEMO
- Construction of DEMO
- Demonstration of electricity generation
- Commercialisation of technologies and materials
- Deployment of fusion together with industry

STAGES



Credit: EUROfusion

ITER: Bringing together the world's tokamak research

PARTNERS

ITER is the cornerstone of the European fusion programme and one of the world's largest and most ambitious scientific undertakings. Seven partners, representing more than half the world's population, bring in their expertise to ensure the success of ITER.

ITER needs thorough preparation and accompanying programmes. Within Europe, a coordinated programme using JET and other tokamaks along with modelling and simulations helps to test and develop ITER operating scenarios, and project and optimise the performance of ITER and design of DEMO. The operation of the JET tokamak with a deuterium-tritium mixture and with an ITER-like wall is key to the preparation of ITER operation.

European researchers also play a key role in the preparation and exploitation of the satellite tokamak JT60-SA in Japan to complement the above mentioned activities in support of ITER and DEMO. All of these activities optimise the ITER research plan and shorten the experimental time towards full performance in ITER.

Any long-term programme must guarantee an uninterrupted handover to the next generation. Therefore, the roadmap takes into account knowledge management and the necessary high quality education and training programme for the "ITER and DEMO generation".

ITER – the way to fusion energy

The ITER International Organization comprises China, Europe, India, Japan, Russia, South Korea and the United States.

At its highest performance 500 MW of fusion power will be generated in the plasma, while only 50 MW of power will be injected into the plasma chamber. ITER will not generate any electricity, but demonstrate magnetic confinement fusion at near power plant size and test technologies vital for the next step, DEMO.

Credit: EUROfusion

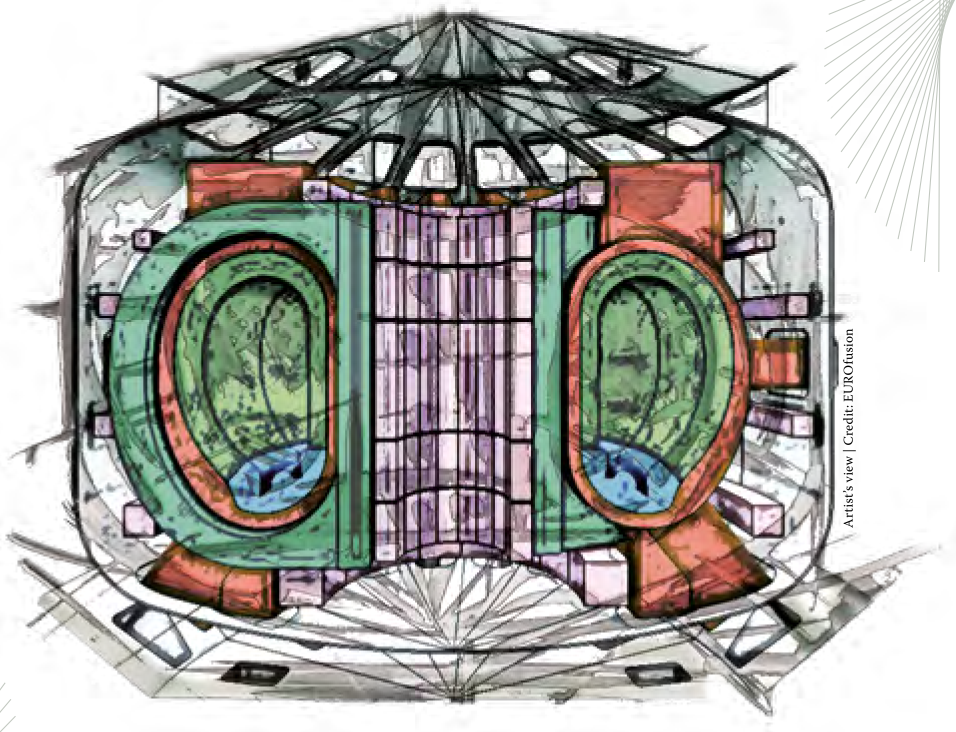
DEMO: Integrating science, technology, and innovation

ITER is providing and will continue to provide vital information for DEMO but this is not sufficient. There are important differences between ITER and DEMO, which require a comprehensive and integrated Research & Development programme. DEMO represents the last step driven by the research community. After DEMO, industry will lead fusion power plant production with limited involvement of the research community.

The roadmap recognises that to realise any electricity-generating power plant a holistic approach is required. All the systems need to be considered and integrated in an industrial approach providing a framework to drive innovation in areas that will have significant impact on performance, reliability, maintainability, capital and lifetime costs.

The road to DEMO construction is divided into three stages. In the first, the pre-conceptual design seeks out options that are developed, compared and assessed. These are narrowed down for the second stage, the Conceptual Design Activity from which a single overall concept is taken into the third stage, the Engineering Design Activity leading to a construction decision. Valuable know-how from industry and Fusion for Energy will become available as ITER construction comes to an end, and the planning of DEMO will be optimised to take advantage of this.

DEMO has two additional goals compared to ITER; electricity production and fuel self-sufficiency. These are essential features for a fusion power plant that, along with the development and qualification of neutron-tolerant materials, require a specific Research & Development programme. The roadmap defines all the major actions for this programme; one of these is the fusion materials test facility, IFMIF-DONES. Materials testing and development is a long lead activity and must provide essential data for DEMO and fusion power plants. Research & Development as well as prototyping is being conducted together with Japan. The provision of this facility is a major milestone for the programme.



Conceptual design drawing of the European DEMO tokamak.

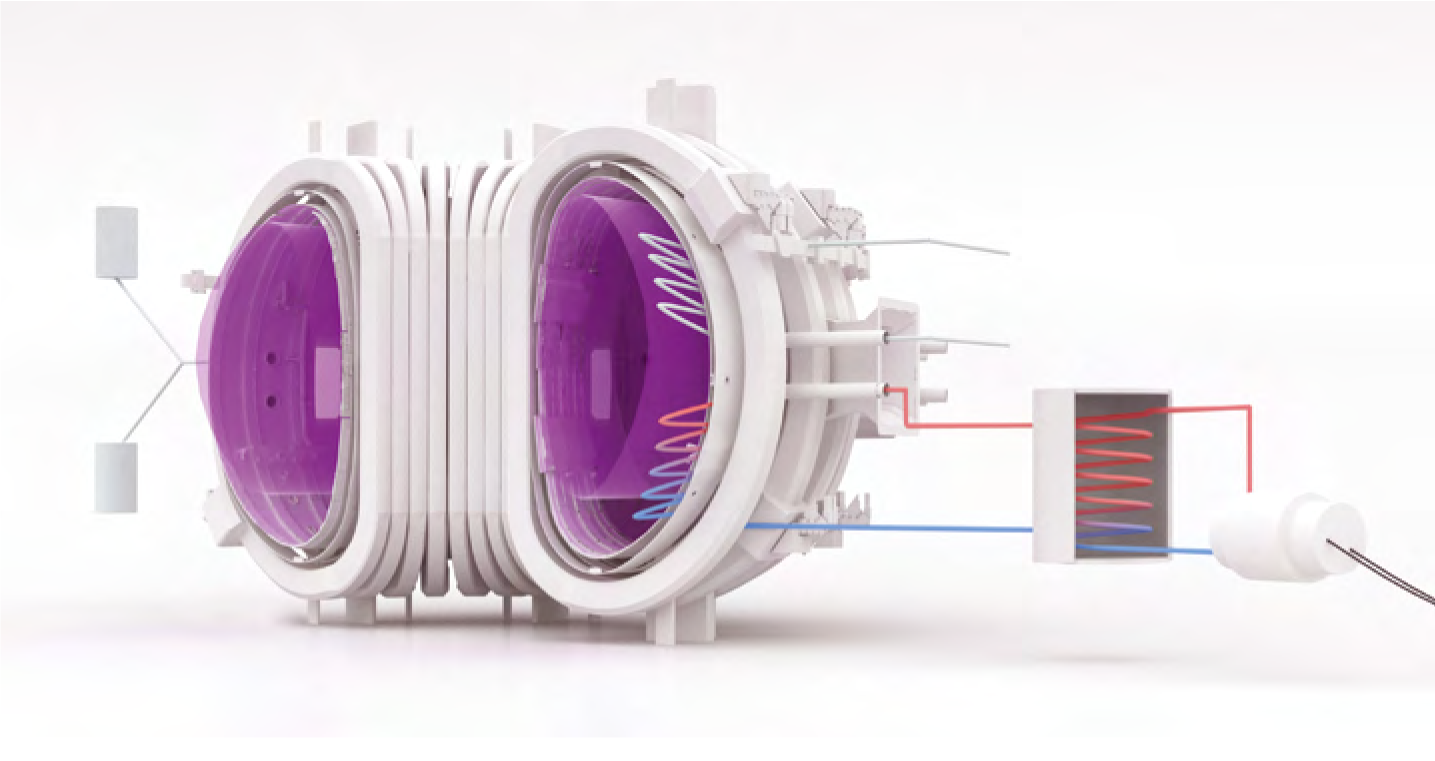
Effective organisation of the Research & Development effort is a key factor. The roadmap recognises that with DEMO the fusion programme is transitioning from a science-driven programme to a project-oriented approach. This transition can only be mastered in close collaboration with industry and all stakeholders. To this end, representatives of the nuclear power sector and other industrial branches are being progressively included into the activities for DEMO.

Industrial knowledge and technology development from the construction of ITER has to be used to grow a European industry and power sector capable of leading in licensing, construction and operation of fusion power plants within and outside Europe.

Fusion presents a special opportunity to provide a long-term robust supply of low-carbon electricity as part of the energy mix in Europe and worldwide. Fusion distinguishes itself from other low-carbon electricity sources such as solar and wind in that it is not intermittent and is suited as a base-load electricity provider in regions and under conditions where this is required.

The roadmap outlines an approach to address the significant remaining scientific, engineering and industrial challenges, many of which have synergies with other science and technology fields. Europe has a leading position in the international fusion research community and has developed expertise in all relevant areas, so it is well placed to implement the roadmap. Fusion is an international endeavour as exemplified by ITER, and Europe will continue to engage strongly with its international partners.

The ambition is high. The rate of progress and success will all depend on the resources and stakeholder support, and the increasing engagement of and innovation in industry. With strong support it is expected that fusion electricity can be generated in Europe early in the second half of this century, leading to the introduction of commercial fusion power plants as part of a future energy mix.



Credit: EUROfusion

POWER PLANT

From prototype to power plant

Artist’s view of a fusion power plant

Further reading & credits

[1] Communications on the Energy Union:

- Communication from the Commission: 'A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy', COM(2015) 80 final, 25/02/2015.
- Communication from the Commission: 'Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation', C(2015)6317 final, 15/09/2015.

See also reference to fusion in the ESPAS (European Strategy and Policy Analysis System) report: 'Global Trends to 2030: Can the EU meet the challenges ahead?' ISBN 978-92-79-38394-6, 2015.

[2] ITER is Latin for 'The way'.

[3] There are ideas for different DEMO-class devices in several of the ITER Parties. In this document we assume that Europe will develop its own DEMO.

[4] The Broader Approach agreement is concluded between EURATOM and Japan. It complements the ITER project through three projects: the Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility , the International Fusion Energy Research Centre, and the Satellite Tokamak Programme Project JT-60SA, which is about half the linear size of ITER.

[5] EUROfusion is a consortium of 30 National Fusion Research Laboratories from 26 European Union countries (plus Switzerland and Ukraine). About 150 universities in these countries are involved as Linked Third Party in the fusion research effort.

[6] The fusion roadmap is a living document that is reviewed in response to scientific and technological discoveries, the budgetary situation, new opportunities, and other developments, www.euro-fusion.org/eurofusion/roadmap.

[7] Fusion for Energy industrial policy principles and objectives, http://fusionforenergy.europa.eu/aboutfusion/decisions12.aspx

[8] Wendelstein 7-X in Germany is the world's largest stellarator and its successor, if built, could be the first stellarator with a deuterium-tritium plasma

Imprint

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In 2018 the European Fusion Community finalised the 'European Roadmap to the Realisation of Fusion Energy' which outlines the steps to the realisation of fusion electricity. The same year the EUROfusion General Assembly approved the document. Additionally, the Euratom Scientific and Technical Committee reviewed the roadmap and supported it with a positive opinion paper. The Governing Board of Fusion for Energy welcomed the initiative, which is in line with the European Council conclusions of April 12th 2018. This document gives an overview of the more detailed roadmap, both can be downloaded at www.euro-fusion.org/eurofusion/roadmap.

EUROPEAN CONSORTIUM FOR THE DEVELOPMENT OF FUSION ENERGY

REALISING FUSION ELECTRICITY

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Laboratory for Plasma Physics
BELGIUM

Bulgarian Academy of Sciences
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