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IAEA WORLD FUSION OUTLOOK 2024

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OUTLOOK
2024

“The journey to fusion energy is a testament to human ingenuity and perseverance.”

IAEA Director General, Rafael Mariano Grossi

The momentum behind fusion energy today is undeniable. Inspired by this progress, I launched the IAEA World Fusion Outlook last year, which serves as a comprehensive global reference that tracks the latest developments in fusion energy. I am very happy with the positive response that this publication has received.

The journey to fusion energy is a testament to human ingenuity and perseverance. To further support this journey, I established the World Fusion Energy Group — a global initiative dedicated to fostering collaboration across the spectrum. Our mission is both ambitious and clear: to accelerate the research, development, demonstration and deployment of fusion energy. By bringing together industry, government, academia and regulatory bodies, we are laying the groundwork for a cohesive fusion energy community, united in the pursuit of common goals.

Governments are playing a crucial role in this endeavour. Strategic public investments, robust policy support and international collaboration are essential to transitioning fusion energy from the laboratory to the grid. The success of the global fusion community hinges on these sustained efforts. I encourage establishing regulatory frameworks that are proportionate to the risks and that provide the necessary clarity to accelerate the development of fusion energy and attract investment in the sector.

This year I also invited a group of international experts to identify a set of fusion key elements that will provide a comprehensive road map and valuable guidance in the short and medium term to scientists, engineers, regulators, entrepreneurs, policy makers and stakeholders worldwide.

As we enter a crucial phase for fusion energy, we must intensify our efforts across all sectors: developing enabling technologies and materials, strengthening public–private partnerships, leveraging private capital for commercial viability and cultivating a global workforce. Fusion energy demands a wide range of expertise, from skilled workers to professionals in law, policy and communications, all of whom contribute to the global economy.

Investing in fusion energy research and its commercialization promises significant economic benefits, far beyond the potential for decarbonization. The spin-off technologies from fusion have applications in healthcare, space propulsion, industrial imaging, geothermal drilling and nuclear waste management, among other applications, opening new business avenues beyond energy generation.

As we navigate the complexities of this groundbreaking technology, our resolve is steadfast: to harness the power of fusion energy for a sustainable, prosperous and peaceful world. The fusion era is no longer just an aspiration; it is a reality within our grasp and together we will make it happen.

This year’s edition of the IAEA World Fusion Outlook goes beyond simply tracking developments and key achievements; it highlights emerging plant concepts, projected development timelines, policy frameworks and trends in both public and private investment. It also covers research output metrics and offers regional and sectoral outlooks. I am confident that the IAEA World Fusion Outlook will continue to serve as a valuable guide for stakeholders in the energy, policy and research sectors as they work to advance fusion energy.■

IAEA Director General Rafael Mariano Grossi speaking in Belgium in March 2024.

"The development of fusion energy is a potential turning point in the long term and a major instrument for a sustainable future of peace and security."

Antonio Tajani,
Vice President of the Council, Minister of Foreign Affairs and International Cooperation

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Antonio Tajani, Vice President of the Council, Minister of Foreign Affairs and International Cooperation of Italy (courtesy of the Government of Italy).

Fusion energy: An unprecedented challenge, an opportunity for the future

We are honoured to co-organize and host the inaugural ministerial meeting of the World Fusion Energy Group. This event reflects the Italian Government's support for international cooperation, and our longstanding commitment to technological advancement: a key driving force to growth, well-being and prosperity.

Energy security is a priority in the current scenario of growing geopolitical turbulence. From a political perspective, fusion energy has the great potential to answer these challenges and ensure energy independence, while reducing the geopolitical tensions linked to the exploitation of fossil fuels. I also think of better access to electricity in large areas of the world still lacking efficient electricity infrastructures.

Developing new technologies in the nuclear sector may be a major step along the path towards energy transition and the fight against climate change. Nuclear energy has been included in the European Union's taxonomy as a clean energy and I believe that we cannot miss the opportunity offered by the beginning of the new European legislature. To reduce our reliance on fossil fuels, we must consider a diverse energy mix in which fusion power coexists with renewables, hydrogen and emerging nuclear technologies like small modular reactors. This will also have a positive impact on energy costs, increase the competitiveness of our enterprises and foster growth.

In other words, the development of fusion energy is a potential turning point in the long term and a major instrument for a sustainable future of peace and security.

The push for innovation and increasing investments are about to make fusion energy a reality. Italy wants to remain at the forefront of this effort, thanks to the know-how of its many public and private entities involved.

The technological, scientific and financial effort is key. It is crucial to promote international cooperation and public–private partnerships, in order to gather the much needed large investments and bring advanced infrastructures and highly specialized expertise into common use. This is also the goal of the World Fusion Energy Group, whose role is crucial to prevent such a scientific effort from turning into a new arena of geopolitical competition.

Italy has always been at the forefront of technological research and innovation in the field of nuclear energy, starting with the development of the first nuclear reactor, which allowed the Italian physicist Enrico Fermi to lay the foundations for modern nuclear physics.

> “The push for innovation and increasing investments are about to make fusion energy a reality.”

Today our National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), is a leading institution in the field of fusion energy, and its research centre in Frascati is a clear example of a virtuous partnership between the public, private and academic sectors.

I also think of our leading energy companies, which brought our innovation effort beyond national borders, participating in many innovative projects.

Italy is ready to share its expertise and contribute to a significant reduction of the knowledge divide between industrialized and developing countries. Academic collaboration, education, and vocational training are at the core — together with the involvement of the private sector — of our new approach towards our development partners, especially in Africa. This is a stance which is also at the centre of the Italian G7 Presidency and our action at the European level.

This is very important because the new era of nuclear and fusion energy depends on young scientists and engineers working to the best of their abilities.

The road ahead is long and complex and the stakes are high. We must be conscious that the choices we make today will shape the social, economic and geopolitical landscape of the future world.

Let's work together to achieve a bright future for the next generation.■

We all recognize the need for a permanent solution to the global challenges of climate change and energy security. To achieve this, we must build a solid path towards decarbonization and consider our existing commitments in climate, energy and environment policies. This includes reaching net zero greenhouse gas emissions by 2050 to limit the global temperature rise to 1.5°C. At the same time, we need to transform our economic and social systems by focusing on net zero emissions, circular economies and climate resilience, all the while ensuring sustainable and inclusive growth, enhancing our economies and accelerating the energy transition.

It is worth reaffirming the importance of science driven approaches in policy making to tackle the global climate and environmental crisis. This requires a neutral technological approach that explores every solution to meet the increasing global energy needs for sustainable development.

Fusion energy has the potential to provide a lasting solution to this challenge. Successful fusion energy production could offer significant social, environmental and economic benefits as a potentially zero emission, safe, secure and virtually unlimited source of clean energy. The prospect of commercializing future fusion plants has led to demonstration facilities being developed over the next decade, driven by large research programmes funded by governments, the European Union and companies worldwide. International collaboration will accelerate fusion technology development and demonstration, reinforcing the need for global engagement to solve research challenges and developing international supply chains and workforces.

The global fusion energy sector is witnessing significant acceleration, with an increasing number of private companies engaged in the development of both magnetic and inertial fusion, or mixed approaches, which attract substantial investments from private entities and governments. Some companies plan to build fusion plants capable of producing electricity between 2040 and 2050, ahead of the mid-century timeline envisaged by public research programmes. In the coming years, the ITER

Gilberto Pichetto Fratin, Minister of the Environment and Energy Security of Italy (courtesy of the Government of Italy).

"We all recognize the need for a permanent solution to the global challenges of climate change and energy security."

Gilberto Pichetto Fratin
Minister of the Environment and Energy Security

project will provide valuable insight into commissioning, plasma scenarios, tritium management and nuclear aspects, plant safety and availability, remote handling, power exhaust and radioactive waste management. The ITER project has already provided relevant information on many of the construction technologies of the plant components and subsystems for fusion electricity production. Recently, ITER announced plans to expand its public–private partnership approach by involving private sector companies in fusion initiatives, with the participation of companies active in fusion plant development, end users, supply chains, universities and research centres. The ITER project, along with the development of new machines, underscores the need for supply chain involvement from the beginning of the design process to optimize experience and skills.

During the G7 Summit under the Italian presidency, the leaders of the seven Member States, recalling a commitment in the G7 Climate, Energy and Environment Ministers' Meeting communiqué (Turin Communiqué), included fusion energy among the areas of collaboration to address global challenges with a commitment to establish the G7 Working Group on Fusion Energy. This further demonstrates the growing recognition of fusion energy's important role in achieving long term energy security and climate goals.

On 21 September 2023, I established the National Platform for Sustainable Nuclear, tasking main scientific organizations and companies operating in the nuclear field to develop a possible roadmap for reconsidering nuclear power generation as a decarbonized and deliverable energy source as part of Italy's energy mix. The Platform has assessed the utility and feasibility of enabling nuclear energy in Italy from 2035 onwards, to support the full deployment of renewables, and in parallel focused on fusion energy, in terms of research and development and its deployment in the medium to long timeframe.

Consequently, based on nuclear data and analysis by the National Platform for Sustainable Nuclear, the Italian National Energy and Climate Plan includes reconsidering nuclear energy as part of Italy's energy mix, incorporating sustainable fission technologies, such as small modular reactors, advanced modular reactors, and microreactors, alongside a possible fusion energy contribution starting around 2050.

Although Italy ceased nuclear energy production almost 40 years ago, public research entities and industries have continued to invest in and develop research on nuclear technologies — including fusion energy. Italy can now therefore capitalize on the existing scientific and technical expertise and capabilities of its research organizations, academia, companies and established industries to foster a robust fusion industry as part of a cohesive national framework.

The Government of Italy is committed to the development of fusion energy science and technology. Under the guidance of the Ministry of Environment and Energy Security, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) already coordinates 21 national partners, including research entities, universities and leading companies, to foster advancements in fusion technology. Italian companies have secured over €1.5 billion in contracts for the development of systems and components for ITER, including in the preparation for ITER operations and its next steps.

Recently, the state owned company RSE also started working on developing materials for inertial confinement fusion; thanks to this expertise, RSE is establishing itself as an important international partner in fusion energy development.

Italy hosts multiple experimental fusion research facilities, including ENEA's research centres in Frascati, near Rome, and in Brasimone in the northern Apennines; the RFX Consortium in Padua; and ISTP-CNR in Milan. These facilities all significantly contribute to scientific progress in fusion energy. The new Divertor Tokamak Test research facility is being built at the ENEA research centre in Frascati, as part of a public–private consortium among ENEA, the energy company Eni and various Italian institutes and universities, to demonstrate the divertor technology for future fusion facilities.

Eni was one of the first energy companies to invest in fusion technology, becoming a strategic shareholder in Commonwealth Fusion Systems in 2018, aiming at accelerating fusion industrialization.

To find solutions for the remaining challenges in demonstrating fusion energy feasibility, we must widen the scope of international collaboration by seeking new partnerships to enhance research and development, encouraging public–private partnerships and driving innovation and resource sharing in fusion development.

As fusion transitions from a scientific endeavour to an industrial reality, and considering the efforts still needed to fill technological gaps, it is essential that we continue to support the positive climate of collaboration and infrastructure sharing that has so far characterized global fusion efforts. Clear intellectual property frameworks for fusion plant processes and products are needed to enable effective technology transfer and support the global growth of the fusion market.

At the same time, I would like to emphasize the importance of developing new regulatory approaches to ensure a high level of safety proportional to fusion's very limited hazards. These approaches should take into account the innovation of this emerging technology, so that fusion plants can be deployed and operated safely. International collaboration among governments, the IAEA and the respective safety authorities is essential for a coordinated approach to regulation among fusion-forward countries and provides the fusion sector with the level of predictability and confidence that it needs.

Italy's geographical location could allow it to become a Mediterranean fusion energy hub in the future — as part of the 'Piano Mattei', the Mattei plan — positioning itself as a leader in addressing regional energy security and sustainability challenges, and in promoting capacity building. Italy is ready to share its broad knowledge and expertise to support countries such as Algeria, Egypt, Morocco and Tunisia in advancing fusion technology. Targeted workforce development and educational programmes can provide entry points for developing skills that can then be expanded to fusion applications.

Italy boasts an almost unique combination of scientific, technological, engineering and industrial skillset, positioning the country to play a leading role in the development and construction of fusion facilities in Italy and Europe.

For these reasons, Italy is proud to co-host the inaugural ministerial meeting of the World Fusion Energy Group (WFEG). The group will act as a catalyst at this critical juncture, where unified efforts are essential to rapidly advance fusion energy development. As the global pursuit of fusion energy gains momentum, the potential of this technology to provide an abundant, clean and sustainable energy solution for the future is becoming increasingly clear, as recognized also by the G7. Recent breakthroughs in fusion have sparked significant interest and investment from a wide range of stakeholders.

The WFEG inaugural meeting in Italy ahead of the COP29 climate conference represents a pivotal moment in the global pursuit of advanced energy solutions. The meeting aims to maximize the impact and visibility of fusion energy discussions within the larger framework of international climate negotiations. The WFEG will not only emphasize the importance of scientific advancements in fusion energy, but also facilitate international cooperation and investment in this transformative technology, aiming to play a crucial role in shaping the future of energy to ensure global climate goals are met and to secure sustainable energy production in the long term.

Italy looks forward to advancing fusion energy on a global scale and is committed to supporting and funding research and innovation in this sector. Italy's vibrant fusion energy programme will involve numerous Italian research organizations, academia, industries as well as international collaboration with the IAEA.

Italy welcomes and will continue to strongly promote the work of the IAEA and its Member States in fusion energy.■

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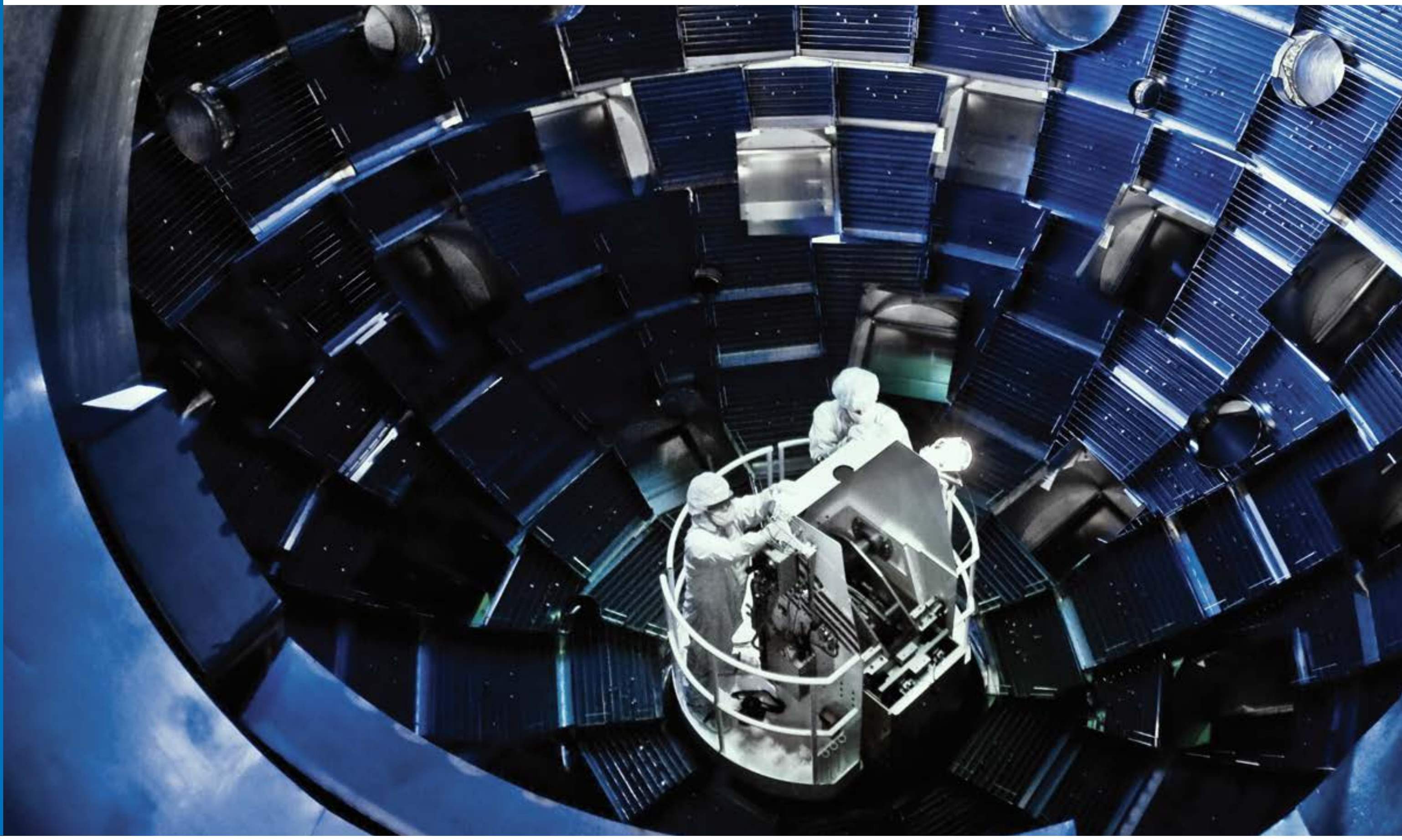
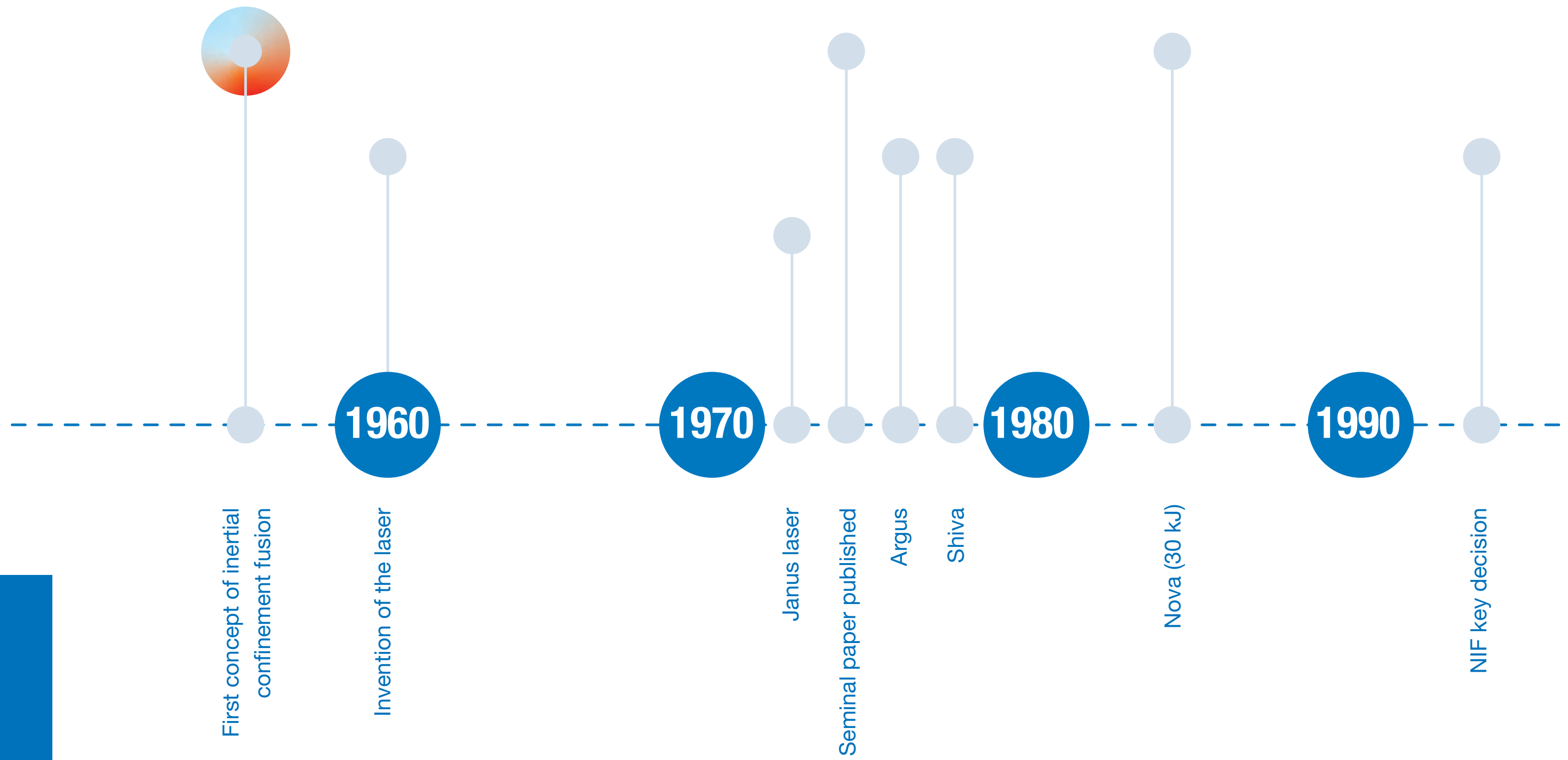
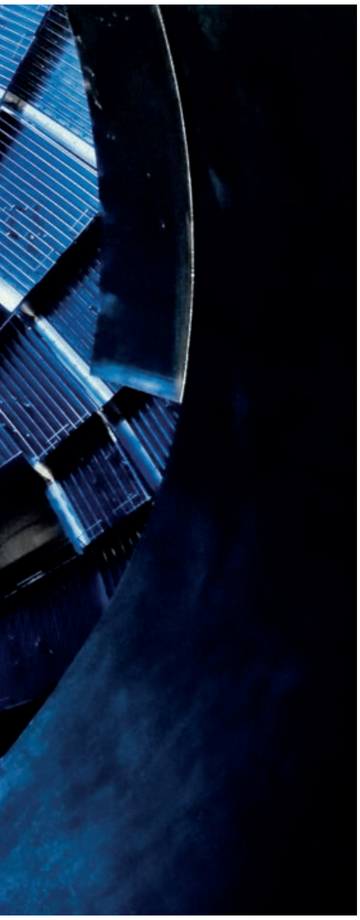
Recent advancements and breakthroughs




First concept of inertial confinement fusion
1960
Invention of the laser
1970
Janus laser
Seminal paper published
Argus
Shiva
1980
Nova (30 kJ)
1990
NIF key decision

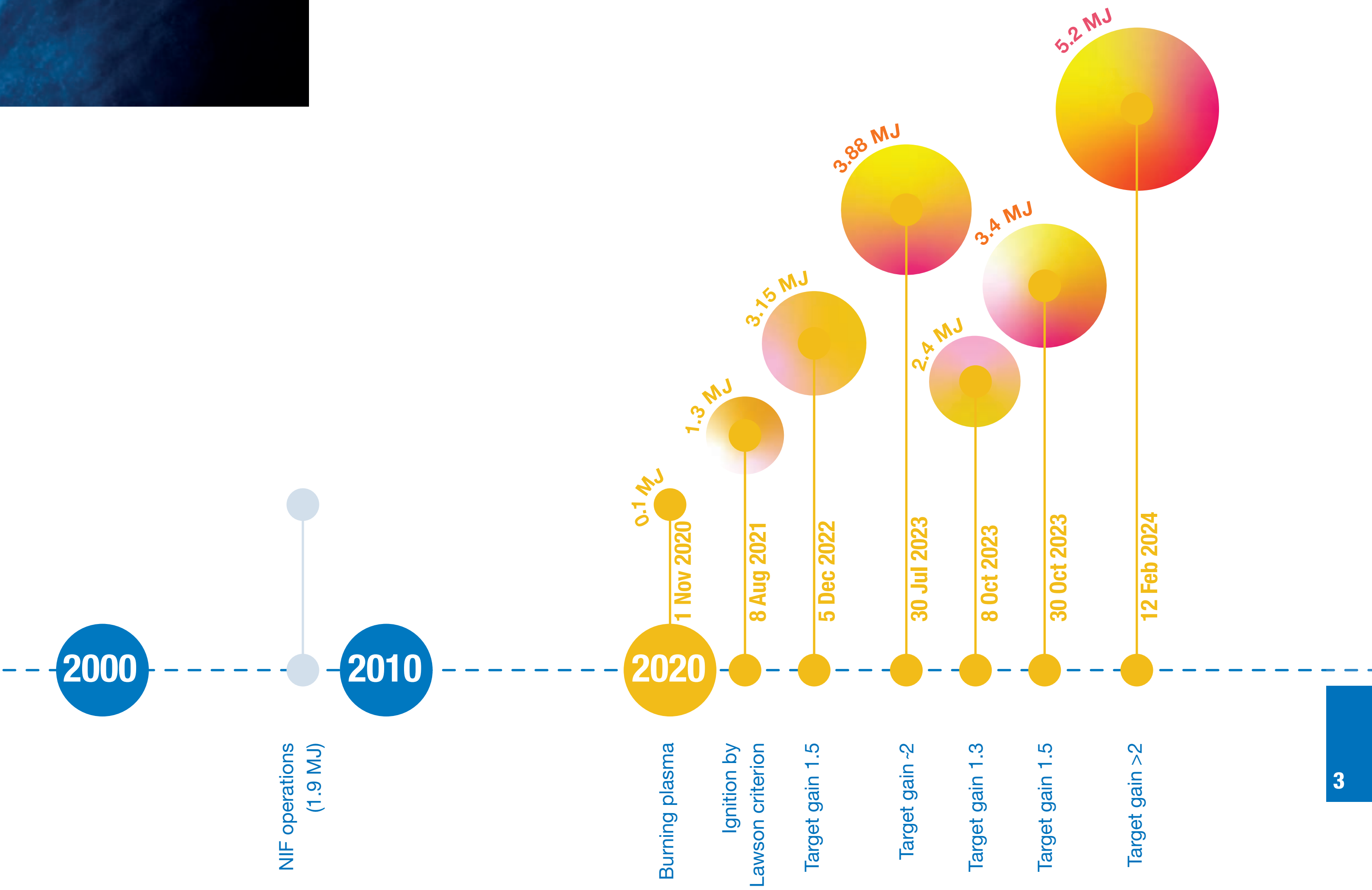


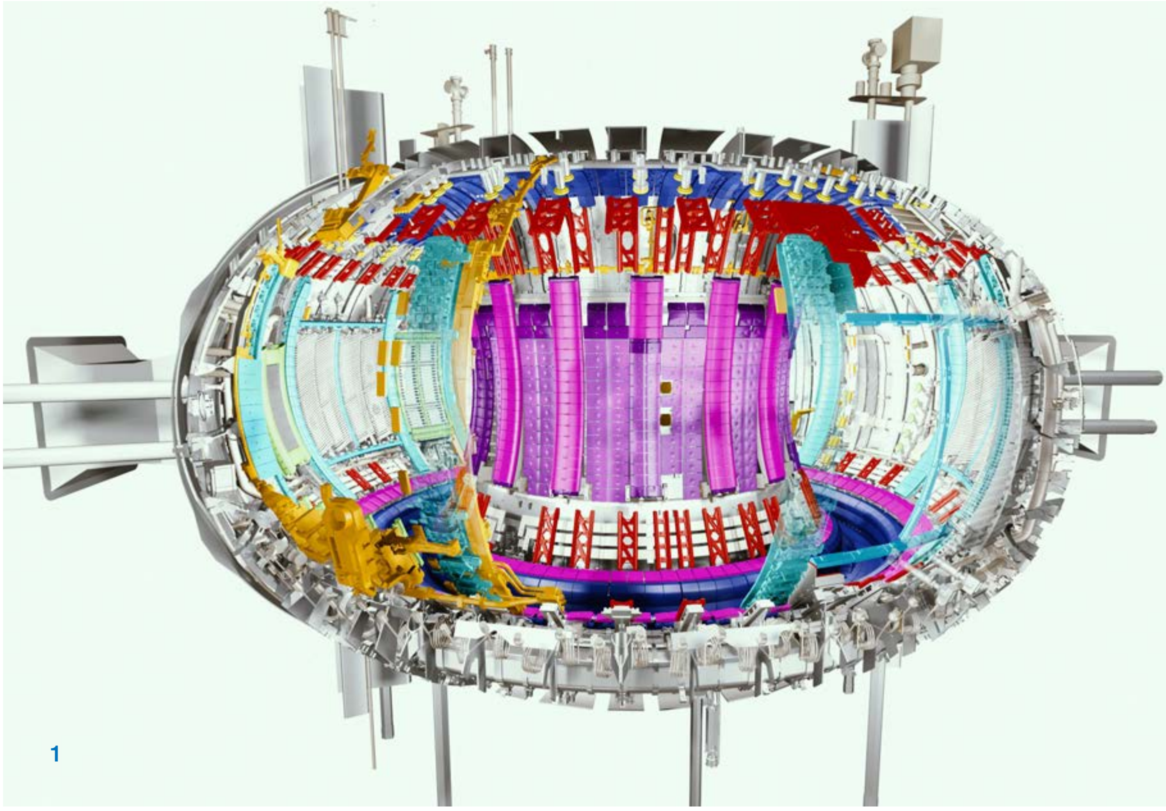
NIF repeats ignition four times

Progress continued at the National Ignition Facility (NIF)

Since the fusion energy ignition breakthrough in December 2022 [1], researchers at the Lawrence Livermore National Laboratory in the United States of America (USA) have successfully replicated this achievement at least four times. Four subsequent experiments in 2023 and early 2024 repeated ignition. The most recent produced a record yield of 5.2 MJ and a gain greater than 2.■

NIF at the Lawrence Livermore National Laboratory in the USA (courtesy of Lawrence Livermore National Laboratory, USA).





JET achieves world record and starts decommissioning

Following 40 years of operation and the final deuterium–tritium experiments conducted throughout 2023, the decommissioning of the Joint European Torus (JET) has begun and will continue until around 2040. Decommissioning JET will provide valuable information for the fusion community by enabling analysis of how the in-vessel materials changed over time during operation.

In its final experiments in December 2023, JET achieved a groundbreaking milestone [2]. Scientists set a world record by maintaining sustained fusion for 5 seconds, generating 69 MJ of energy with minimal fuel. They explored innovative techniques, such as inverting the plasma shape to enhance its confinement. Additionally, they intentionally directed a high energy beam of electrons, produced during plasma disruptions, at the inner wall to advance the understanding of beam control and damage mechanisms.■

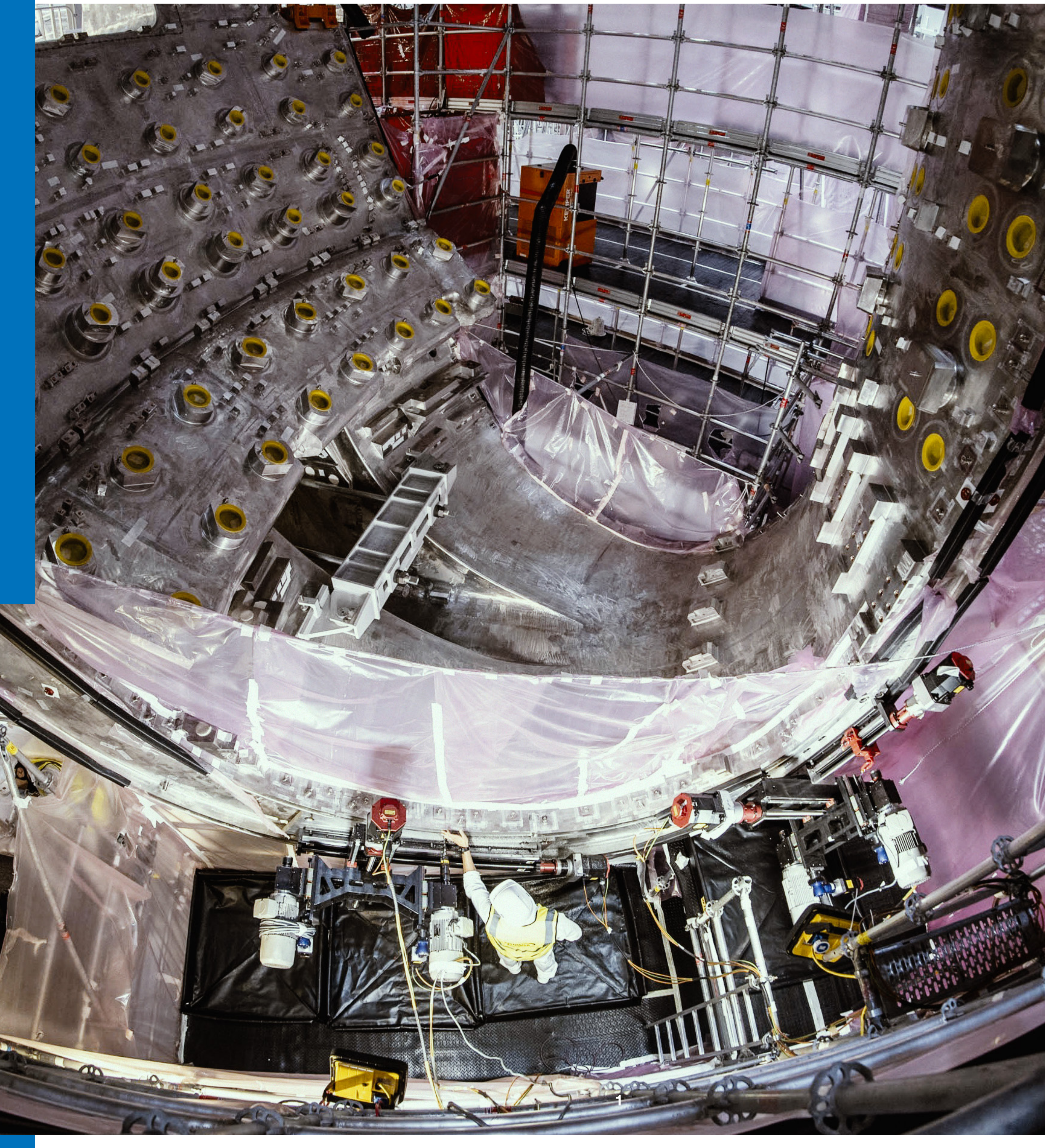
1 View of JET in-vessel cables, components and systems (courtesy of United Kingdom Atomic Energy Authority (UKAEA), United Kingdom).

2 Aerial view of the ITER site as of July 2024 (courtesy of ITER, France).

ITER progresses to new baseline

The ITER project has gone through a period of transition and is moving forward on a new project baseline. Repairs to key components are progressing according to schedule. Progress has continued on construction, manufacturing, assembly and system commissioning. Following more than a year of review, a new baseline proposal was submitted to the ITER Council in June 2024, and now serves as the working reference schedule.

The discovery and analysis of geometric non-conformities in the bevel joints of several vacuum vessel sectors, as well as chloride corrosion cracking in the cooling pipes of the thermal shields, led to a slowdown in the ITER tokamak assembly while repairs were made. In parallel, an assessment of root cause including a self-examination of project quality culture led to a reorganization to prepare for the challenges ahead. Extensive discussions were held with the French Nuclear Safety Authority to enhance the safety demonstration accompanying ITER's licensing. Meanwhile, the power supply systems, cryogenics plant and cooling water system have been installed and are largely commissioned. All poloidal and toroidal field coils have been delivered as well as most of the central solenoid modules and other major components.■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The largest task over the past year has been to channel these elements into a realistic updated project baseline.

The previously envisioned stages of assembly and operation are consolidated in the resulting proposal. Technical and operational risks are mitigated by incorporating the divertor, shield blocks, a sacrificial first wall and other risk reducing components into a more complete machine before initial operation, as well as fully testing some toroidal and poloidal field coils before installation.

The start of research operations in 2034 will inaugurate a 27 month period of substantial experimentation with hydrogen and deuterium–deuterium plasmas, to culminate in operating the tokamak in long pulses at full magnetic energy and plasma current (15 MA) in 2036.

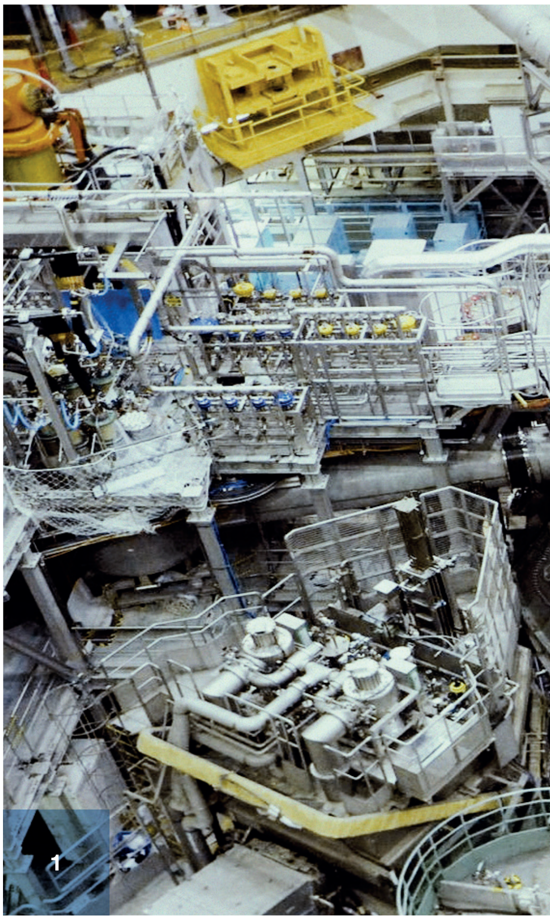
The start of the research operations phase will largely demonstrate the integration of systems needed for industrial scale fusion operations. The start of the deuterium–tritium operations phase will be delayed by four years from the previous baseline from 2035 to 2039.■

◀ Metrology is playing an essential role in the repair of ITER vacuum vessel sectors, including in the positioning, with micrometric precision, of the milling machines responsible for shaving off excess material and returning the component to nominal (courtesy of ITER, France).

2034 Start of experiments with hydrogen and deuterium–deuterium plasma

2036 Start of long pulse operation at full magnetic energy and plasma current

2039 Start of deuterium–tritium operations

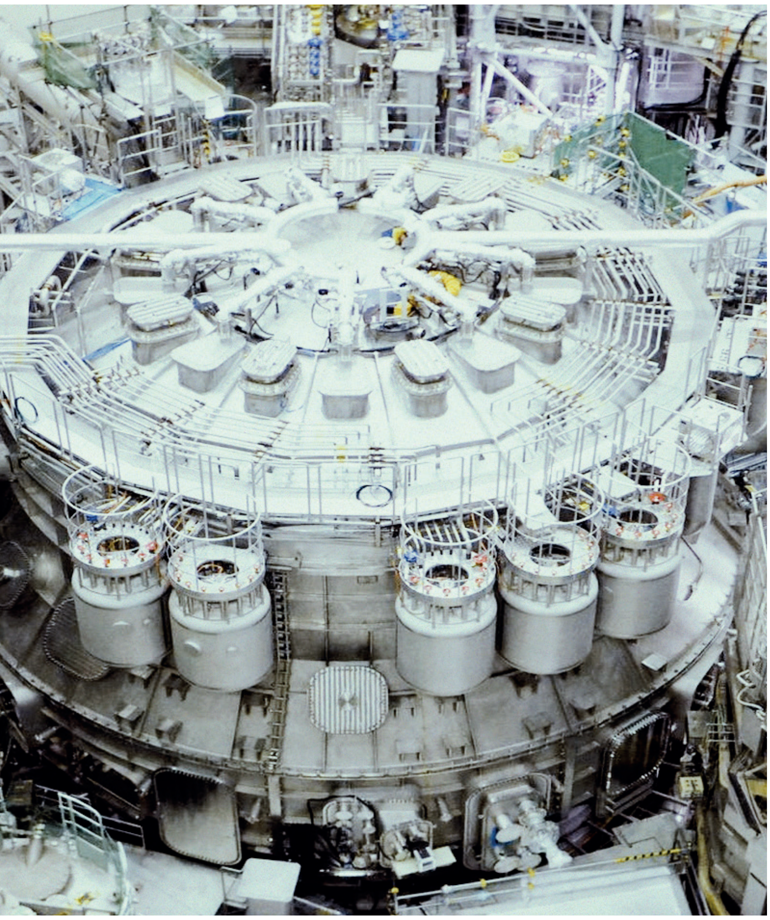


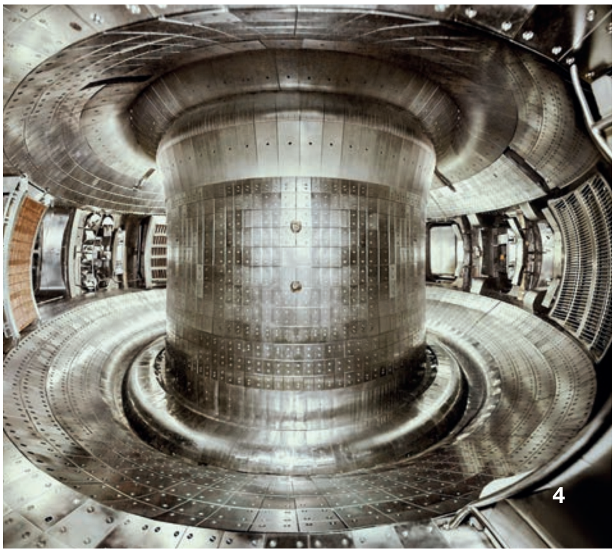
More progress since the first IAEA World Fusion Outlook

The JT-60SA tokamak produced its first plasma [3]. The four storey tall machine is designed to hold plasma heated to 200 million degrees Celsius for about 100 seconds, far longer than previous large tokamaks. Plasmas in the JT-60SA will closely resemble those planned for ITER and should allow physicists to study plasma stability and how it affects fusion power output at long timescales, providing lessons that can be applied to next step tokamaks. Elsewhere in Japan, the Linear International Fusion Materials Irradiation Facility (IFMIF) Prototype Accelerator has been installed in Rokkasho, Japan.■

The EAST tokamak in China achieved a steady state high confinement long plasma operation for 403 seconds [4]. This achievement improved on the original record of 101 seconds, which was set by EAST in 2017. The temperature and density of particles were greatly increased during the high confinement plasma operation, which will improve the power generation efficiency of future fusion power plants. Also in China, the HL-3 tokamak operated for the first time in high confinement mode with a plasma current of one million amperes, owing to upgraded heating, operation, control, diagnostic and power supply systems.■

Researchers at the Korea Institute of Fusion Energy, working on the Korea Superconducting Tokamak Advanced Research (KSTAR), set a record by reaching a temperature of 100 million degrees Celsius for 48 seconds and sustained high plasma confinement mode for over 100 seconds. This achievement follows their previous milestone of maintaining high plasma confinement for 30 seconds in 2021, marking a significant advancement in fusion energy research. KSTAR aims to sustain plasma temperatures of 100 million degrees for 300 seconds by 2026. In line with ITER's decision to replace the beryllium divertor with tungsten, KSTAR is now operating with a tungsten divertor.■



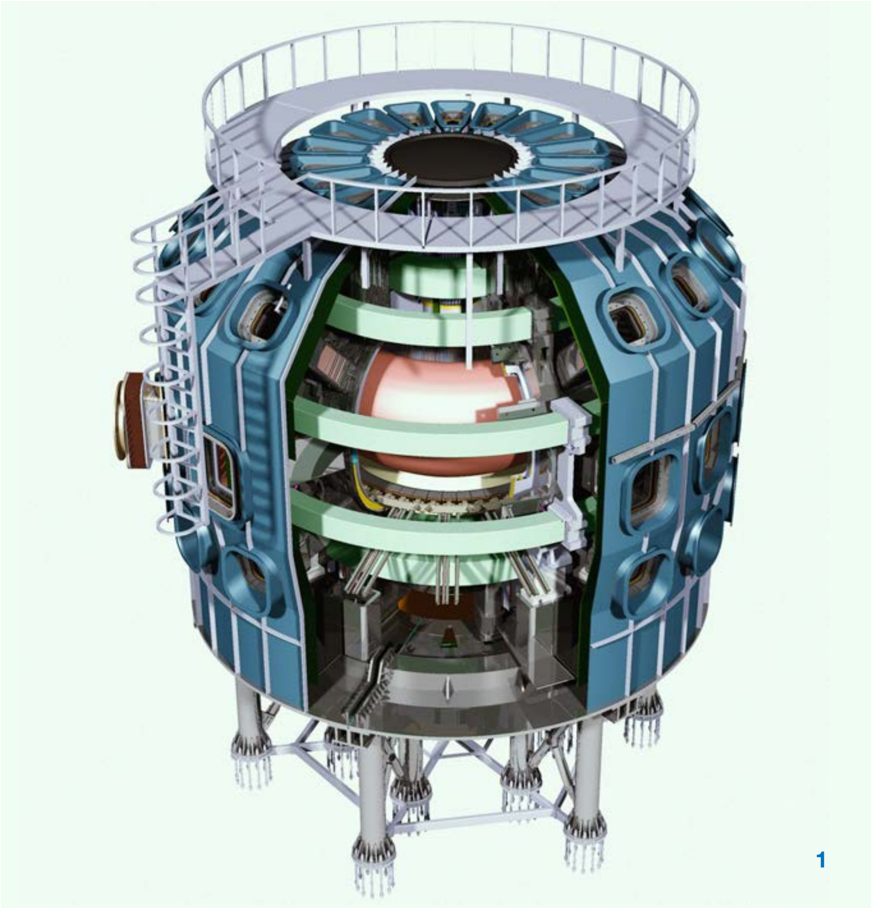


1 JT-60SA is the largest tokamak in operation, designed and built jointly by Japan and the European Union (EU) (courtesy of the National Institutes for Quantum Science and Technology, Japan).

2 KSTAR tokamak at the Korea Institute of Fusion Energy (courtesy of Korea Institute of Fusion Energy, Republic of Korea).

3 IAEA Director General Rafael Mariano Grossi visits the Linear IFMIF Prototype Accelerator at the Rokkasho Fusion Institute during his visit to Japan (courtesy of the National Institutes for Quantum Science and Technology, Japan).

4 Inside the EAST tokamak (courtesy of the Institute of Plasma Physics, Chinese Academy of Sciences, China).



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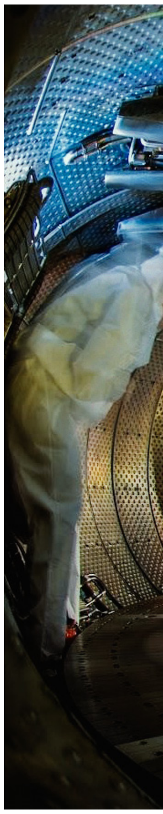
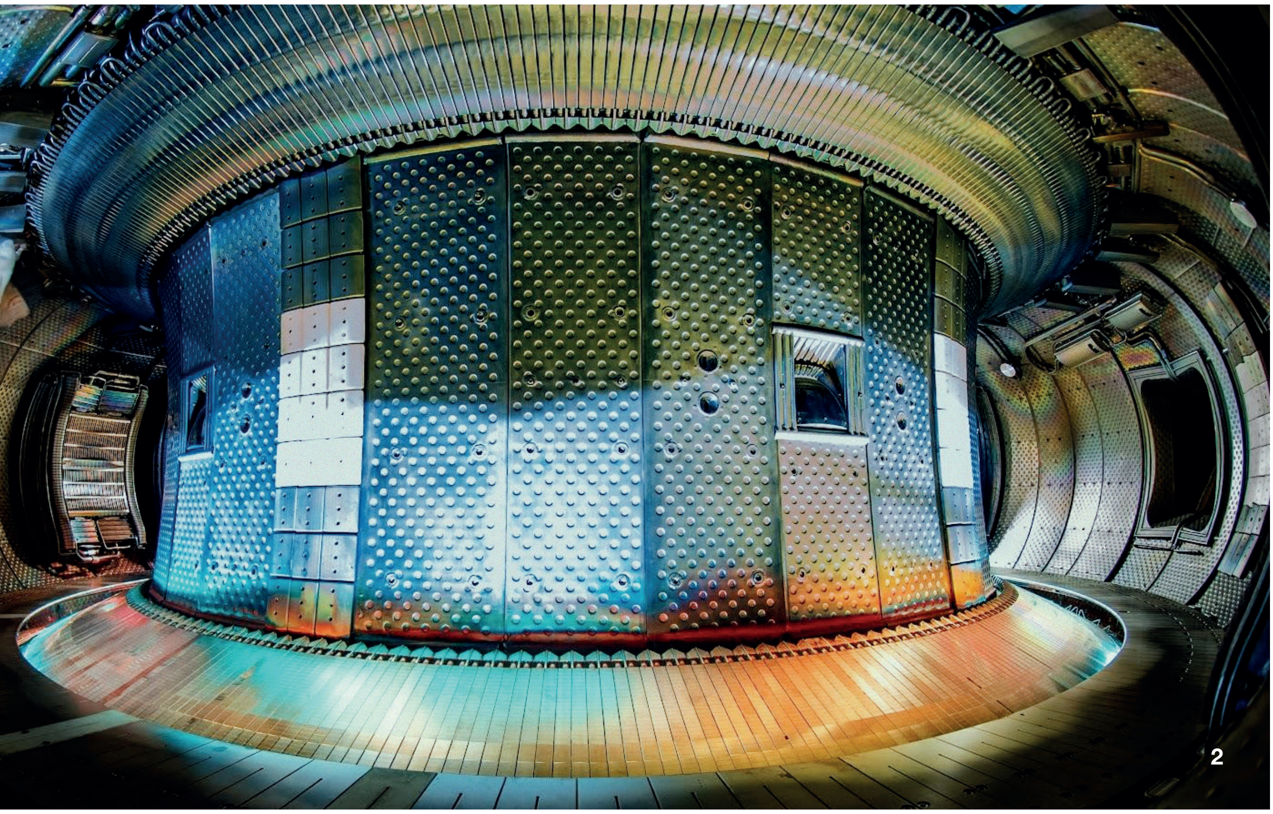


In Italy, progress continued in the construction of the Divertor Tokamak Test (DTT) facility, a new superconducting tokamak devoted to the study of advanced divertor solutions for fusion plants. Composed of many Italian research institutions and international partners, including one of the biggest energy companies in the world, the DTT consortium implementing the project has raised nearly €500 million to construct the facility. The primary mission of the DTT is to explore and test the physics and technology of concepts for plasma power exhaust that could be used in the European Demonstration Power Plant (EU-DEMO).■

Similar to KSTAR, France's WEST tokamak, located at the French Alternative Energies and Atomic Energy Commission site in Cadarache, has also successfully begun operating with a tungsten divertor. During the initial experimental campaign, high neutron fluence was produced through a series of plasma pulses lasting about 1 minute each, demonstrating the durability and performance of this new component. Additionally, in a collaborative effort, researchers at French Alternative Energies and Atomic Energy Commission and at the Plasma Princeton Plasma Physics Laboratory in the USA achieved a significant milestone by maintaining fusion plasma at approximately 50 million degrees Celsius for a record 6 minutes [5]. This breakthrough, which involved injecting 15% more energy and doubling the plasma density compared to earlier attempts, underscores the potential of tungsten clad fusion devices for future fusion plants.■



1 Visualization of the DTT facility (courtesy of the DTT Consortium, Italy).

2 WEST tokamak equipped with its actively cooled tungsten divertor (courtesy of the French Alternative Energies and Atomic Energy Commission, France).

The USA's national fusion facility, DIII-D, operated by General Atomics for the US Department of Energy, has completed major upgrades, including new plasma control systems, advanced diagnostic tools, improved heating and current drive systems and enhancements to the divertor system. These upgrades equip DIII-D with advanced tools to operate in a manner consistent with the needs of a fusion plant. Just before the upgrade, experiments at DIII-D achieved a combination of

1 The SPARC steel vacuum vessel arrived in 2024 (courtesy of Commonwealth Fusion Systems, USA).

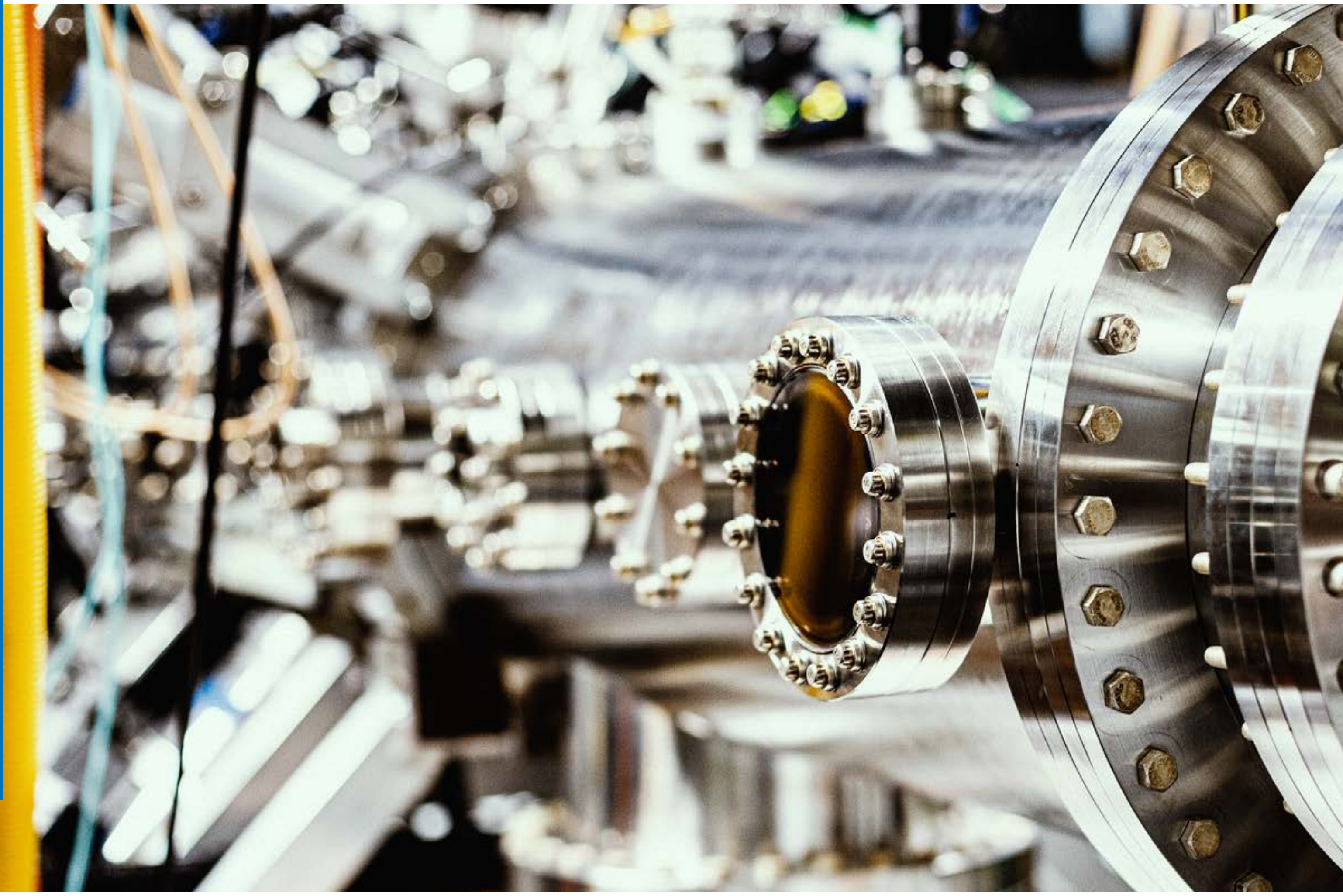
2 IAEA Director General Rafael Mariano Grossi visiting the SPARC tokamak hall ready for machine assembly.

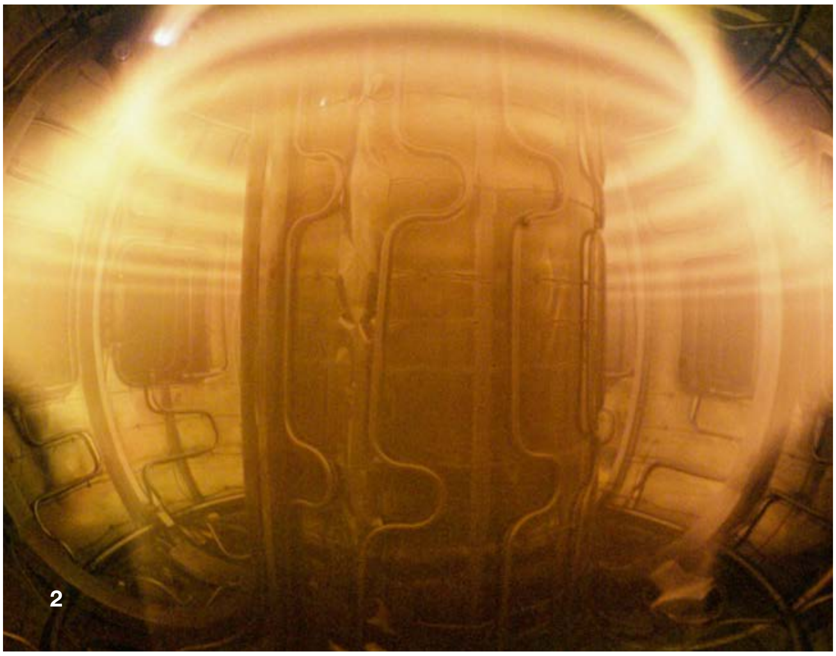
high density and high confinement of the fuel that had never been achieved simultaneously [6]. This operating regime supports critical requirements in many fusion plant designs worldwide and opens a potential pathway to producing economically attractive fusion energy. Additionally, in experiments at DIII-D, researchers at the Princeton Plasma Physics Laboratory demonstrated that their artificial intelligence (AI) model, trained solely on past experimental data, could forecast potential plasma instabilities, known as tearing mode instabilities, up to 300 milliseconds in advance [7]. The AI controller was able to predict and avoid instabilities before they appeared, paving the way for a controller that could support a stable, high powered plasma regime in real time in fusion plants.■

Advancements have steadily progressed at Commonwealth Fusion Systems (CFS) on the construction site for SPARC, a tokamak planned to generate a net scientific energy gain. A significant milestone was reached with the arrival of the vacuum vessel. SPARC is anticipated to become operational in 2025 and demonstrate net scientific energy gain. Following SPARC, the successor project, ARC, is expected to be completed by the mid-2030s, aiming to demonstrate electricity production.■

3 An engineer inside DIII-D installing new diagnostic equipment (courtesy of General Atomics, USA).

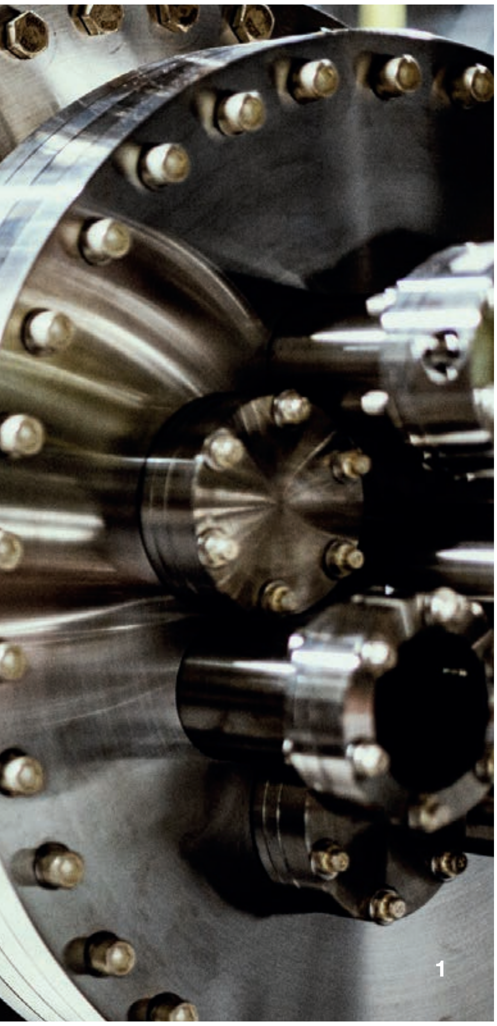
AI for Plasma Control in Fusion Energy by AI for Good





1 Zap Energy's Fusion *Z*-pinch Experiment, known as FuZE (courtesy of Zap Energy, USA).

2 Inside the HH70 tokamak which started operating in June 2024 (courtesy of Energy Singularity, China).



Zap Energy's Fusion *Z*-pinch Experiment, known as FuZE, has achieved plasma electron temperatures in the range of 1–3 keV [8], exceeding 10 million degrees Celsius. The performance of this machine has advanced to a level comparable with the world's leading fusion experimental devices. Concurrently, the development of a fusion plant based on the same technology is also underway.■

The pioneering high temperature superconducting (HTS) tokamak developed by Energy Singularity, HH70, has achieved its first plasma. This device features a toroidal magnetic field of 0.6 T and a major radius of 0.75 m and a system of 26 HTS magnets. Looking ahead, Energy Singularity is planning its next generation high field HTS tokamak, HH170, which aims to achieve a deuterium–tritium equivalent energy gain greater than 10.■

Fusion plants

At least 20 fusion plant concepts are at various stages of development in Canada, China, Germany, Israel, Japan, the Republic of Korea, the Russian Federation, Sweden, the United Kingdom (UK) and the USA with the target completion dates ranging between the late 2020s and mid-2050s.

These concepts are being developed by individual governments, private companies and some public–private joint ventures.

CRITERIA FOR A SUCCESSFUL FUSION PILOT PLANT [9, 10]

Category	Criteria
Fusion and electric power performance	1. 100-500 MW net fusion time-averaged thermal power 2. ≥50 MW(e) peak electricity generation 3. $Q_e > 1$ 4. Operate for several environmental cycles[a]
Components	5. Strategy, cost and timescale of removing and replacing degraded components as a design feature
Fuel and ash	6. Ash removal concept can be scaled up to a first of a kind fusion plant 7. Plasma facing components that can withstand damage caused by helium ash in an environment representative of first of a kind fusion power plant 8. Tritium breeding ratio >0.9 9. Tritium inventory ≤1 kg 10. Innovations in boundary plasma science, fuelling technologies and gas processing 11. Tritium accountability clearly defined along with analytical methods that can satisfy accountability requirements
Reliability and availability	12. Perform remote maintenance and replacement 13. Modular, replaceable components
Environmental and safety considerations	14. Mitigation of tritium release 15. Minimizing waste volume and hazard overall and avoiding greater than class C waste as much as feasible 16. Decommissioning of activated waste
Economics	17. Overnight construction cost of less than US $5-6 billion

[a] An environmental cycle in a fusion plant includes installing core components, operating the plant until these components degrade, and then performing maintenance to continue operations. Although the duration of this cycle is not precisely defined and can differ by design, it typically spans about a year of full power operation before maintenance or repair is needed in a first of a kind fusion power plant.
Note: Criteria in grey are for deuterium–tritium based fusion plants.

General Fusion Plant (General Fusion, Canada)

General Fusion aims to build the world's first magnetized target fusion plant by the early to mid-2030s. Owing to a liquid metal liner in the fusion machine mechanically compressed by an array of pistons, fusion conditions are created in short pulses rather than creating a sustained process. This unique design, which does not need superconducting magnets or an array of lasers, aims to address material degradation, fuel production, energy capture and cost barriers to commercialization. In the current design, a General Fusion power plant would produce about 300 MW(e) from two 150 MW machines running in tandem to provide cost competitive, zero carbon electricity.

In January 2024, peer reviewed results confirmed that General Fusion can produce the smooth, rapid and

+1

2025

Electric Fusion Systems

+9

2030

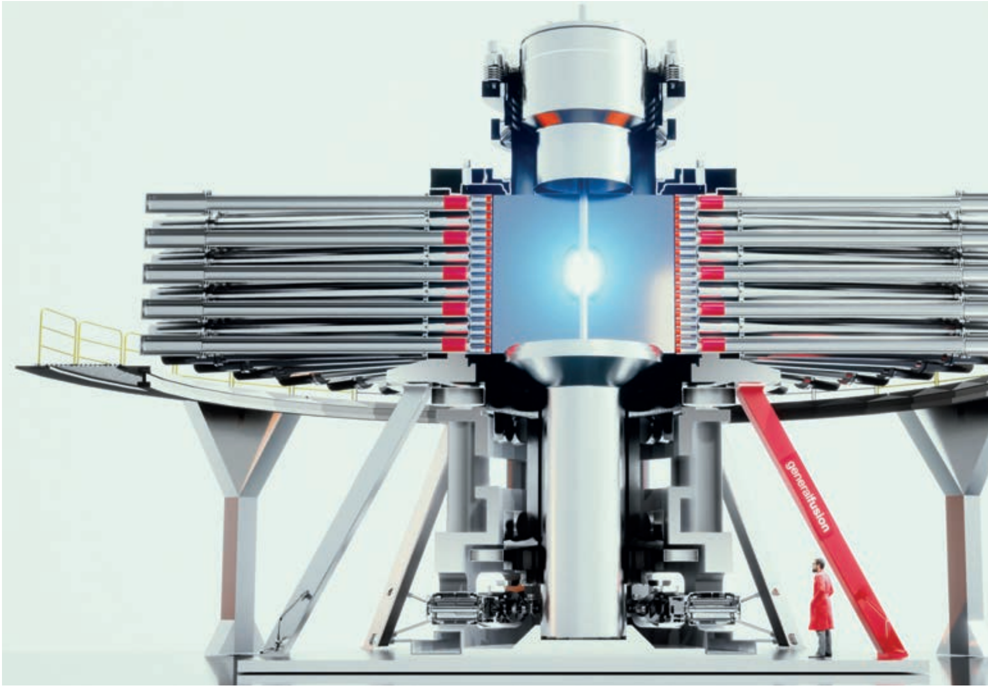
Avalanche Energy, Blue Laser Fusion, Helion Energy, Kyoto Fusioneering, LPPFusion, Magneto Inertial Fusion Technologies, nT-Tao, Openstar Technologies, Princeton Fusion Systems

+27

2035

Acceleron Fusion, Commonwealth Fusion Systems, Deutelio, Ex-Fusion, First Light Fusion, Fuse, General Atomics, General Fusion, HB11 Energy, Helical Fusion, Longview Fusion Energy Systems, Marvel Fusion, Nearstar Fusion, NK Labs, Novatron Fusion Group, Openstar Technologies, Proxima Fusion, Realta Fusion, Renaissance Fusion, Stellarex, TAE Technologies, Terra Fusion Energy Corporation, Thea Energy, Tokamak Energy, Type One Energy Group, Xcimer Energy, Zap Energy symmetrical compression of a liquid cavity needed for a commercial power plant. In March 2024, the company also made breakthroughs in modelling the liquid metal liner in a commercial machine by developing a proprietary code, which enables the testing of various designs and configurations for a power plant.

General Fusion is building an experimental fusion machine called Lawson Machine 26 (known as LM26) to achieve technical breakthroughs that will derisk and fast track the path to a power plant. LM26 is designed to achieve fusion conditions of over 100 million degrees Celsius by 2025 and scientific net energy by 2026. The data gathered from LM26 will be incorporated into the design of the company's planned commercial scale machine. ■



A concept of what LM26 may look like (courtesy of General Fusion, Canada).

+5

2040

Chinese Consortium, ENN Science and Technology Development, Focused Energy, LaserFusionX, UK Industrial Fusion Solutions

+4

2045

Gauss Fusion, Neo Fusion, Japanese Consortium, Shine Technologies

+3

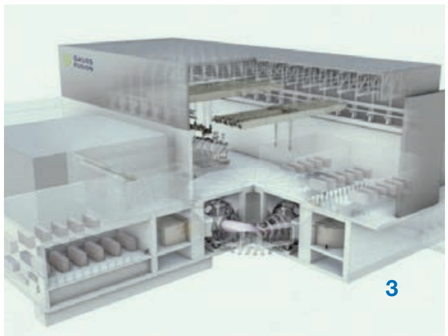
2050

EUROfusion, Korean Consortium, Indian Consortium

+1

2055

Russian Consortium



1 A possible layout for the EU-DEMO fusion plant (courtesy of EUROfusion, Germany).

2 An artist’s impression of the China Fusion Engineering Test Reactor (courtesy of University of Science and Technology of China, China).

3 A rendering of Gauss GIGA (courtesy of Gauss Fusion, Germany).

China Fusion Engineering Test Reactor (Chinese Consortium, China)

The China Fusion Engineering Test Reactor (CFETR) is a fusion plant concept based on a conventional tokamak design currently being developed in China by a national consortium. The CFETR is the next device in the roadmap for the realization of fusion energy in China. Construction is expected to be completed by 2040. The CFETR is expected to bridge the gaps between ITER and a fusion plant, as well as to demonstrate net electricity gain and a duty factor of 0.5. The CFETR research and its development plan will consist of two phases. During the first phase, the efforts will focus on achieving steady state operation and demonstrating tritium self-sufficiency with fusion power up to 200 MW. This phase will address issues relevant to burning plasma physics research and development to ascertain the feasibility of steady state advanced operation. The second phase will focus on validating plant relevant technology with fusion power above 1 GW. A key product of the second phase is the construction of a RAMI[1] database for the design of a commercial plant. Some conceptual features of the CFETR are: major radius of 7.2 m, minor radius of 2.2 m, plasma elongation κ_{95}=2, plasma current of 14 MA, magnetic field on axis of 6.5 tesla, normalized beta β_N=2.3 and a predicted scientific energy gain Q_{sci}=20.■

EU-DEMO (Eurofusion, EU)

The EU-DEMO is a fusion plant concept based on a conventional tokamak design being developed in Europe by EUROfusion. EU-DEMO is the facility expected to follow ITER in the European roadmap to electricity from fusion. The project is currently in its conceptual design phase and is expected to start operating by 2050. EU-DEMO aims to demonstrate the technological and economic viability of fusion energy by producing about 500 MW(e) of net electricity, achieving tritium self-sufficiency. Several design options are being studied. These options will have an impact on several plant technologies, including the divertor configuration and breeding blanket solutions, among others. The pre-conceptual design of EU-DEMO foresees a major radius of ~9 m and fusion power of ~2 GW. Attention is now focused on minimizing the machine size and technical risks to facilitate earlier deployment.■

Gauss GIGA (Gauss Fusion, Germany)

Gauss Fusion aims to design and develop Gauss GIGA, a GW class electric fusion plant based on stellarator designs by 2045. This project will be carried out through a public–private partnership with national and European institutions. The current base design features a relatively high aspect ratio and a cross-section similar to ITER, allowing the use of magnets and vacuum vessels that are within the industry's production, shipping and installation capabilities.

Gauss Fusion plans to accelerate deployment by bypassing the need for intermediate experimental or demonstration devices. This will be accomplished by leveraging a multistage commissioning process for the first of its kind fusion plant. The commissioning is expected to proceed in stages, each designed to gather maximum data and enable ongoing operational extensions and upgrades. The process will start with an initial plasma device, followed by the demonstration of a remote maintenance system, then transition to a tritium capable machine and finally incorporate a fully continuous fuel cycle and electricity generation.

This phased approach is expected to allow for the decoupling of technology development timelines and the fine tuning of parameters, diagnostic systems and control systems. Additionally it would facilitate the collection of critical materials data.■

Proxima Fusion Plant (Proxima Fusion, Germany)

Proxima Fusion focuses on high field quasi-isodynamic stellarators using HTS magnet technology. The company's fusion plant concepts inherit from the groundbreaking Wendelstein 7-X (W7-X) stellarator in Germany, where the principles of quasi-isodynamic optimization and the island divertor approach have been first developed. Proxima Fusion's plant designs rely on HTS technology to reach magnetic field amplitudes that are not accessible to traditional (low temperature) superconducting magnets, using integrated computational design to overcome previous engineering limits on support structures. Proxima Fusion's quasi-isodynamic stellarator designs rely on high frequency electron cyclotron resonance heating and water cooled lithium–lead breeding blankets.■

Tao Machine (nT-Tao, Israel)

nT-Tao is an Israeli startup working on a fusion plant design roughly the size of a shipping container. The system could supply 10 to 20 MW of power to an existing grid or act as a

[1] RAMI stands for reliability, availability, maintainability and inspectability. It describes a process whose primary purpose is to make sure that all the systems of the fusion plant are reliable during the operation phase and maintain their performance under operational conditions with the best possible availability.

remote, independent and scalable energy solution. nT-Tao plans to reach a commercial prototype design by the end of the decade. nT-Tao's solution relies on a proprietary pulse based plasma heating method and a magnetic chamber topology based on a dynamically stabilized torus. nT-Tao's approach aims to reduce the size of the machine which would enable quick development iterations, lower cost and reduce complexity of design.■

Helical Fusion Power Plant (Helical Fusion, Japan)

Helical Fusion aims to develop a steady state fusion plant by 2034, with plans to commercialize it in the 2040s. The plant is based on a heliotron configuration featuring two helical coils and incorporates HTS conductor and liquid metal blanket technologies. The flexible, high current density HTS conductor allows for the construction of compact helical coils. The liquid metal blanket protects all plasma facing walls and enables highly efficient electricity generation. Additionally, the heliotron design offers easier structural maintenance compared to other stellarators, making it particularly suitable for commercialization. These innovations can enable the creation of a compact fusion power plant with an electrical output of 50–100 MW(e).■

JA DEMO (Japanese Consortium, Japan)

JA DEMO is a fusion plant concept based on a conventional tokamak design being developed in Japan. The objectives of JA DEMO are to realize a steady and stable electric output of over several 100 MW(e), tritium self-sufficiency, as well as plant availability bridging the gap to the commercialization of fusion energy. The core principles of JA DEMO include demonstrating the technological feasibility based on ITER's component design and ensuring operational flexibility, ranging from pulsed operation (approximately 2 hours) to steady state operation. JA DEMO's construction is anticipated to be completed by 2045, with plans to demonstrate electrical power generation through pulsed operation shortly thereafter. The second phase aims to achieve steady state operation by 2055. Some of JA DEMO's conceptual features are: fusion power of 1.5 GW, major radius of 8.5 m, minor radius of 2.42 m, plasma elongation κ_{95}=1.65, plasma current of 12.3 MA, magnetic field on axis of 5.94 T, normalized beta β_N=3.4, current drive power of 83.7 MW and a predicted scientific energy gain Q_{sci}=17.5.■

K-DEMO (Korean Consortium, Republic of Korea)

K-DEMO is a fusion plant concept based on a conventional tokamak design being developed in the Republic of Korea. The conceptual design of K-DEMO features a major radius of 6.8 m, minor radius of 2.1 m, toroidal field of about 7 T (with low temperature superconductors) and plasma current larger than 12 MA. The engineering design for K-DEMO is scheduled to be completed by 2035. A recent focus has been on the design space, which has been explored using supercomputing resources to investigate global parameters. Alongside the basic concept, a second path involving a smaller, more advanced design with high temperature superconducting magnets is also being investigated.■

DEMO-RF (Russian Consortium, Russian Federation)

DEMO-RF is a fusion plant concept based on a conventional tokamak design being developed in the Russian Federation by a national consortium. The construction of DEMO-RF is expected to be completed by 2055 with the goal of demonstrating a net electricity gain thereafter. DEMO-RF features are under development. The conceptual design currently foresees the use of the facility either as a pure fusion energy plant or as a fusion–fission hybrid reactor with HTS magnets and a total magnetic field larger than 8 T and plasma current of about 5 MA. Liquid metal plasma facing components are being considered for the first wall and divertor. In addition, the Russian Federation plans to develop a fusion–fission hybrid reactor known as DEMO Fusion Neutron Source. This reactor aims not only to generate energy from fusion but also to utilize fusion produced neutrons to convert non-fissile uranium into fissile nuclear material or to transmute long lived radioactive waste. Scheduled for completion by 2033, the DEMO Fusion Neutron Source is a key component of the Russian Federation's fast track strategy to achieve fusion energy by 2050.■

N4 (Novatron Fusion Group, Sweden)

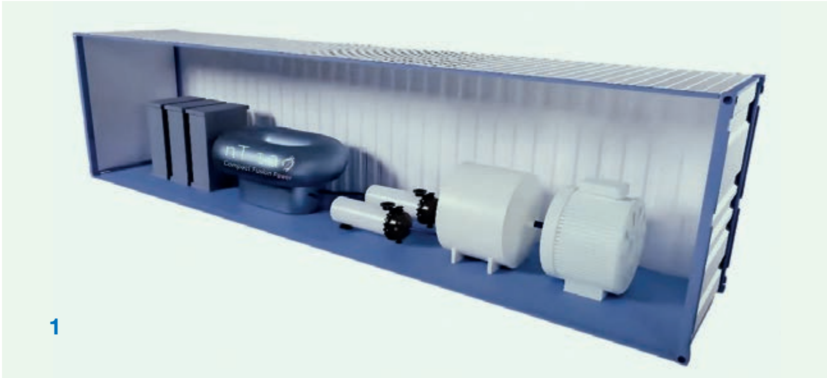
Novatron Fusion Group is developing a fusion plant concept based on conventional magnetic mirror design. The company's roadmap includes the development of two experimental machines (N1 and N2), a pre-commercial demonstration plant (N3) and the first of its kind fusion plant N4. They are currently progressing towards a proof of principle for N1, with the goal of achieving 1.5 GW(e) from N4 by the end of the 2030s. N4 is designed to operate in steady state mode with continuous fuel supply and exhaust gas extraction, allowing for the direct conversion of ionized particles into electricity. Additionally, N4 can be equipped with HTS magnet technology further enhancing its performance and efficiency.■

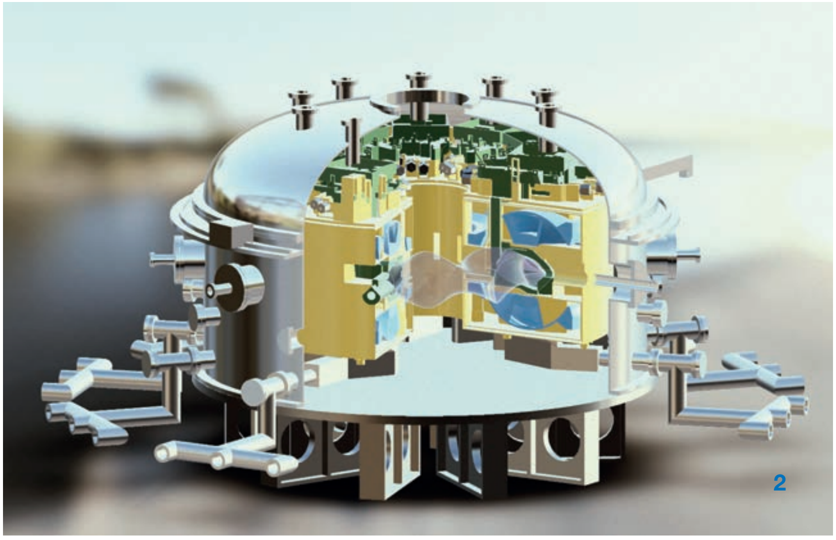
1 A mock-up of the compact fusion power solution, the Tao Machine (courtesy of nT-Tao, Israel).

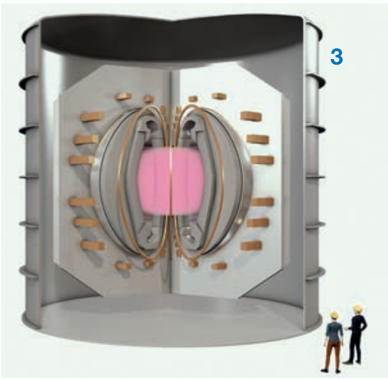
2 Rendering of the Helical Fusion machine (courtesy of Helical Fusion, Japan).

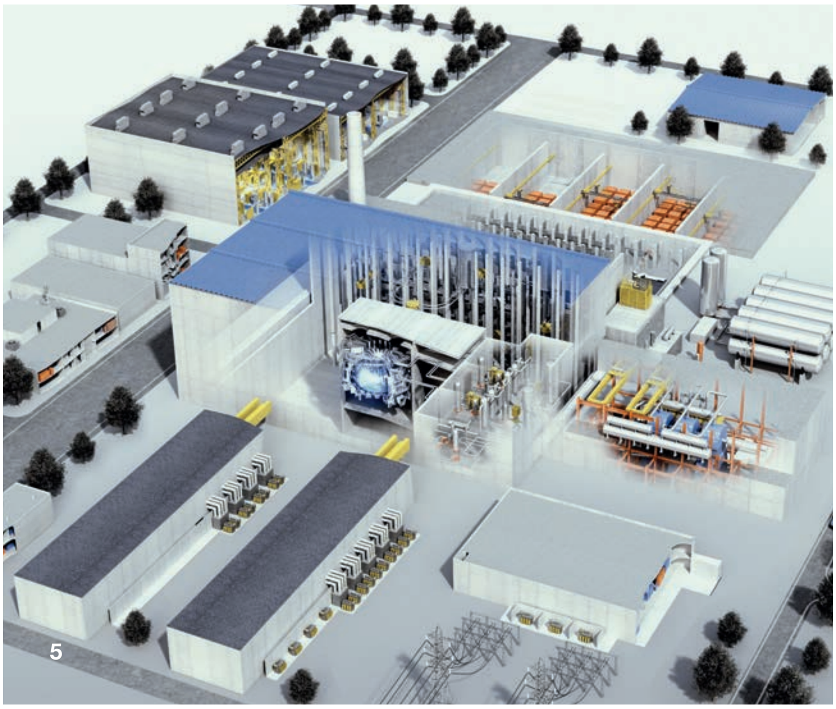
Tokamak Energy Fusion Pilot Plant (Tokamak Energy, UK)

Tokamak Energy's fusion pilot plant aims to integrate, test and demonstrate all the systems necessary for subsequent commercial fusion plants. It is designed as a low aspect ratio tokamak, featuring HTS (rare earth barium copper oxide) toroidal field magnets and aims to demonstrate sustained pulses of burning plasma with net energy output. The project is being designed and developed collaboratively by an international team from the USA and the UK under the US Department of Energy's Milestone-Based Fusion Development Program.■





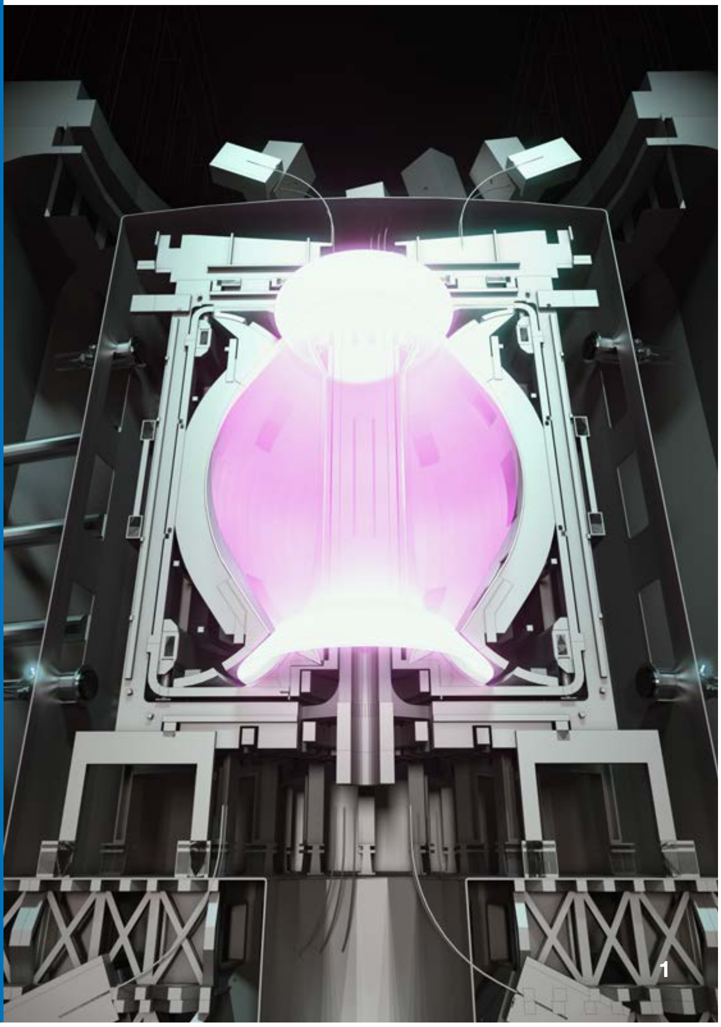




3 A concept of what Tokamak Energy's fusion pilot plant might look like (courtesy of Tokamak Energy, UK).

4 Novatron's N4 fusion plant concept (courtesy of Novatron, Sweden).

5 The JA DEMO concept (courtesy of the National Institutes for Quantum Science and Technology, Japan).



STEP (UK Industrial Fusion Solutions, UK)

The STEP prototype fusion plant aims to demonstrate net energy, fuel self-sufficiency and a route to commercial fusion power, targeting first operations in 2040 [11]. The STEP team has employed a digital set based design methodology, which has undergone multiple concept maturity level reviews and several independent technical advisory group assessments. The concept design carefully balances performance, cost, size and risk, with detailed engineering design set to begin in 2025. UK Industrial Fusion Solutions — a wholly owned subsidiary of the UKAEA Group — will be responsible for the delivery of STEP and will lead a public–private alliance to design and build the plant, which will be located at West Burton, a former coal fired power station site in the north of England. Alongside the plant, STEP's mission includes developing a world leading fusion supply chain to support the commercialization of fusion energy. STEP will build a new supplier infrastructure including whole plant integrators and system manufacturers that can design and deliver future fusion plants worldwide.■

ARC (Commonwealth Fusion Systems, USA)

ARC is a fusion plant concept based on a conventional tokamak design being developed by CFS. The purpose of ARC is to demonstrate the commercial viability of fusion energy with HTS magnet technology. ARC will be a compact conventional tokamak with HTS magnets able to produce ~400 MW(e), with a major radius of ~4 m, a minor radius of ~1.2 m and an on-axis magnetic field of ~11 T. ARC will feature HTS based toroidal field, poloidal field and central solenoid magnet coils. Some of the coils will have joints to enable disassembly for quick replacements of the vacuum vessel, thus mitigating first wall lifetime issues, and enable the possibility of changing vacuum vessel designs and divertor materials in a single tokamak.

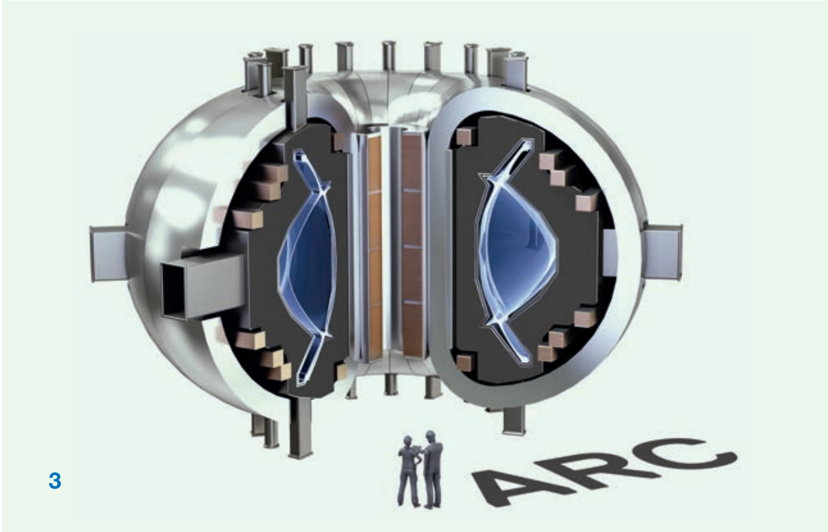
ARC will benefit from information derived and lessons learned from the SPARC tokamak, presently under development (the start of construction was February 2023), expected to finish construction in 2025 and become operational in 2026 and generate a net scientific energy gain. The SPARC tokamak hall has nearly completed

1 STEP is aiming for first operations in 2040 (courtesy of the UKAEA, UK).

2 The GA FPP will rely on advanced sensors, control algorithms and high performance computers (courtesy of General Atomics, USA).

3 ARC will use HTS magnet technology (courtesy of CFS, USA).

2



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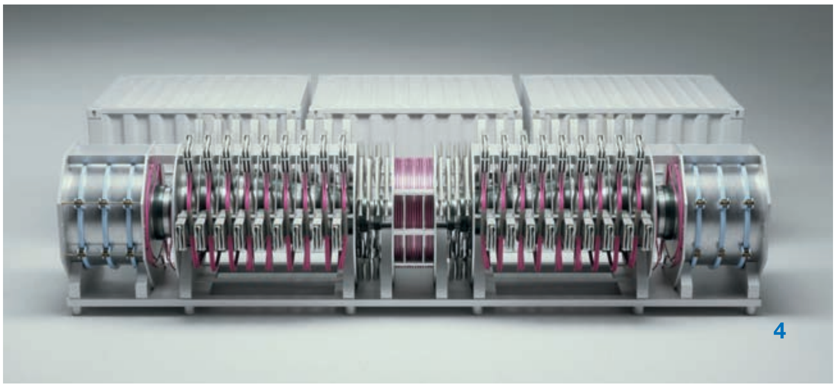

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construction and components of the device have arrived and begun to be assembled this year. CFS has disclosed around US $2.1 billion in funding and currently has over 800 full time employees supporting the construction of SPARC, the manufacturing of HTS magnets in the CFS magnet factory and enabling research and development for ARC.■

GA FPP (General Atomics, USA)

The GA FPP is a fusion plant concept based on a steady state, compact advanced tokamak design, being developed by General Atomics. The design approach will rely on advanced sensors, control algorithms and high performance computers for controlling the plasma, silicon carbide breeding blankets for producing the tritium and microwave heating necessary to power the fusion plasma.■

Polaris (Helion Energy, USA)

Helion Energy has built six fusion prototypes and is currently building its seventh, called Polaris. Polaris marks a significant leap in commercial fusion energy, aiming to be the first machine to produce electricity from fusion. Polaris is being built in a facility half the size of a football field and can be considered Helion's pre-production fusion machine, paving the way for the first commercial fusion plant. Polaris, with a total length of 19 m, is designed to work with deuterium–deuterium, deuterium–helium-3 and deuterium–tritium fuel types.

It will operate at a repetition rate of 0.1 Hz or faster and features a capacitor bank capacity exceeding 50 MJ. The peak field reaches over 15 T, equivalent to about 1000 atmospheres of pressure. Polaris will have 3800 diagnostics and gas filtering systems to gauge its performance and filter its resulting products.■

4 Polaris aims to be the first machine to produce electricity from fusion (courtesy of Helion, USA).

Longview Plant (Longview Fusion Energy Systems, USA)

Longview Fusion Energy Systems aims to develop a fusion plant based on a laser driven inertial confinement design which will be designed together with the Fluor Corporation. This plant will serve as a model for future commercial plants intended to be deployed nationally and internationally.■

SX0 (Stellarex, USA)

Stellarex, a company founded in 2022, is pioneering the development of a fusion plant based on a stellarator design. Collaborating with Ontario Power Generation, industry partners and academic institutions, Stellarex aims to establish a Stellarator Centre of Excellence for fusion energy in Ontario, Canada. The company's goal is to build a stellarator fusion machine, SX0, achieve net energy gain in 2030 and then complete construction of the Stellarex Fusion Power Plant, SX1, capable of producing 600 MW(th) and 250 MW(e) electrical power.■

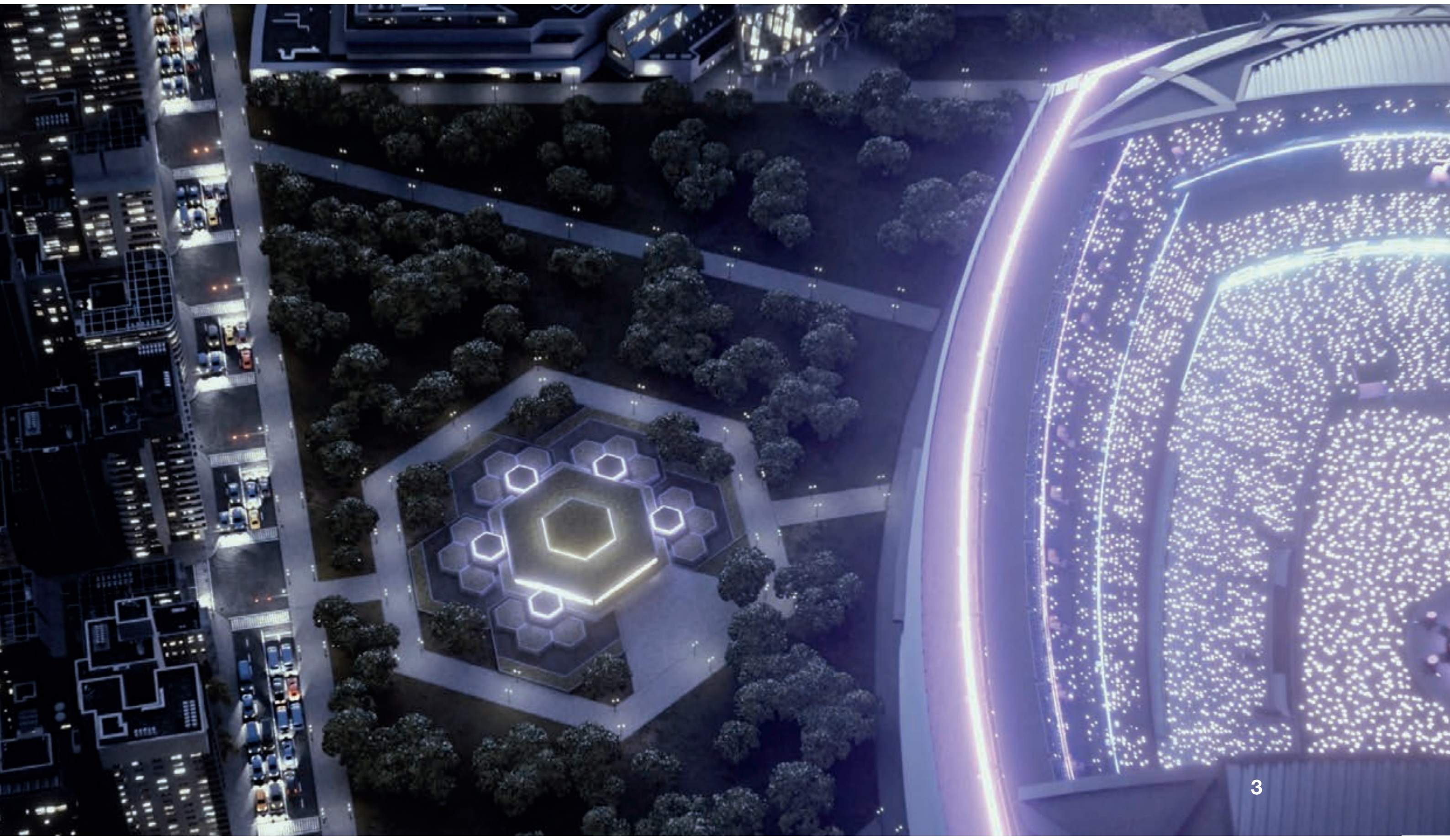
Da Vinci (TAE Technologies, USA)

Since the inception of TAE Technologies, the company has been committed to pursuing fusion with hydrogen–boron. It is safe, plentiful with over 100 000 years of supply and accessible all across the world, however it requires maintaining higher temperatures to produce an energy generating fusion plasma. To achieve these performance levels, TAE Technologies developed a proprietary platform called an advanced beam driven field reversed configuration. This approach combines the deepest insights of plasma physics and accelerator physics to heat and stabilize plasma. In addition, this compact linear configuration enables a physically smaller and therefore more scalable and cost effective device.
The seventh generation device from TAE Technologies, Da Vinci, is expected to be the world's first prototype hydrogen–boron fusion plant, delivering net electrons to the grid in the early 2030s.■

1 The seventh generation device from TAE Technologies, Da Vinci, is expected to be the world's first prototype hydrogen–boron fusion plant (courtesy of TAE Technologies, USA).

2 The Longview Plant will be based on a laser driven inertial confinement design (courtesy of Longview Fusion Energy Systems, USA).

3 The sheared flow stabilized *Z* design in the Zap Plant (courtesy of Zap Energy, USA).



Zap Plant (Zap Energy, USA)

Zap Energy is developing a fusion plant based on a sheared flow stabilized *Z* design. This technology confines and compresses plasma without superconducting magnetic coils or powerful lasers, enabling rapid iteration towards a commercial energy source. Inside a working fusion device, each Z pinch starts with a powerful pulse of electricity released by a bank of capacitors. This pulse jolts a cloud of deuterium gas into a flat ring of hot plasma. The disc races down the device's inner cathode, or negatively–charged end. Once past the cathode's nose cone, the plasma disc coalesces into a tight, sheared flow column, with different layers flowing at different speeds. Flowing liquid metal walls capable of withstanding extreme conditions capture energy from fusion plasma. A mix of lead and lithium in the walls will produce tritium, which will feed back into the plant as fuel. This compact design means a single fusion device can be just 3 m wide and generate roughly 50 MW(e) — enough to power a small city — with Zap Energy power plants likely housing several modules per plant.■

The Role of Fusion Energy in a Decarbonized System

The role of fusion energy in a decarbonized electricity system

Fusion has potential societal value in the trillions of US dollars in a decarbonized world. Deployment scale and timing, as well as operation of fusion plants, are highly dependent on:

- Fusion costs (key cost drivers for fusion plants include equipment cost, regulatory considerations and operations and maintenance costs);
- Cost and availability of alternative low carbon technologies in each region;
- Carbon emission constraints;
- Economic and electricity demand growth;
- Market design.

The ability of fusion to scale requires developing materials and manufacturing capabilities for niche components, which is not the case for raw materials [12].■

Contex scenar

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Highlighting public and private efforts in fusion energy development programmes

Private investments in fusion companies have surged

This surge necessitates global engagement to accelerate scientific and technological development, build supply chains and establish regulatory frameworks.

Governments across the globe are recognizing the potential of fusion energy and are investing heavily in research and development to propel progress. National strategies are being crafted — accompanied by substantial funding allocations — to support both public and private sector initiatives, the development of initial regulatory frameworks and increased engagement with supply chains. Collaborative efforts are also on the rise, with countries entering into agreements to share knowledge, resources and infrastructure to accelerate the path towards commercial fusion energy production. The synergy between scientific breakthroughs and supportive policy frameworks is creating a robust ecosystem aimed at making fusion energy a reality in the near future.

Fusion energy is attracting growing interest from a wide range of stakeholders. The industry has seen a number of agreements established between fusion technology developers and a variety of end users seeking to secure a future source of clean and reliable energy. End users range from the technology industry including companies such as Amazon, Google and Microsoft, which face skyrocketing power demand as their AI systems advance, to fossil fuel energy companies, utilities, supply chain companies, the electric vehicle space and even startups developing direct air capture technology to remove CO_2 from the atmosphere on the path to net zero.■

These efforts align with the global objective of transitioning to sustainable energy sources and deploying fusion as a safe, clean and abundant energy solution worldwide.

IAEA's Fusion Key Elements

Aligning public and private efforts to an industry led fusion energy development programme

Commercial fusion at scale can be part of the future solution for climate, economic and energy security challenges. As fusion energy does not emit CO_2 or other greenhouse gases into the atmosphere, this potential clean energy source is attracting strong market interest and industry investment, in part through public–private partnerships (PPPs) [13].

Advancements and significant progress in fusion science and technology in recent years have triggered the private sector's appetite to advance fusion energy, as public, private and equity investments in fusion projects continue to grow at pace [14, 15]. Several companies aim to achieve commercial applications in the next few years or decades.

Given the substantial financial and technical demands involved in developing viable fusion plants, PPPs are therefore increasingly emerging as a crucial mechanism in fusion energy development. Public resources necessitate the involvement of private investors who can provide additional capital and industry expertise. The significant private investment in fusion technologies, which now exceeds US $7.3 billion globally [15], demonstrates investor interest in developing viable fusion plants in the coming years. Private projects require government support to provide confidence to investors and to leverage the expertise developed in the public sector over years of research and development activities. However, resources remain limited and the need for efficient allocation of these resources is critical. PPPs can help mitigate this challenge by ensuring that both public and private sectors share the risks and rewards. Government funding and support can provide the necessary stability and confidence for private investors, enabling fusion companies to pursue ambitious projects while diversifying any financial risk [16].■

The collaboration between public institutions and private companies enables a more diversified approach to research and development, fostering innovation and accelerating progress by moving in parallel and with quicker timelines [17]. PPPs typically involve sharing project responsibilities between the private sector and the government, with governments often providing guaranteed cash flows while the private sector manages project development, thereby sharing the risk.

When thoughtfully managed, PPPs can be formidable tools in addressing long term capital and political stability challenges [18]. The energy sector has already successfully leveraged the benefits of PPPs and they could be one way to help mitigate climate change [19, 20]. Furthermore, the frameworks for PPPs already exist, as they have been widely applied in other sectors for many years [21].

Building fusion plants does not follow a one size fits all model. It therefore stands to reason that PPPs are inherently flexible, with governments and investors being able to adapt the initiative to the particular circumstances of a country, region or — in some cases — a specific project.■

FUNDING REPORTED IN 2023/2024

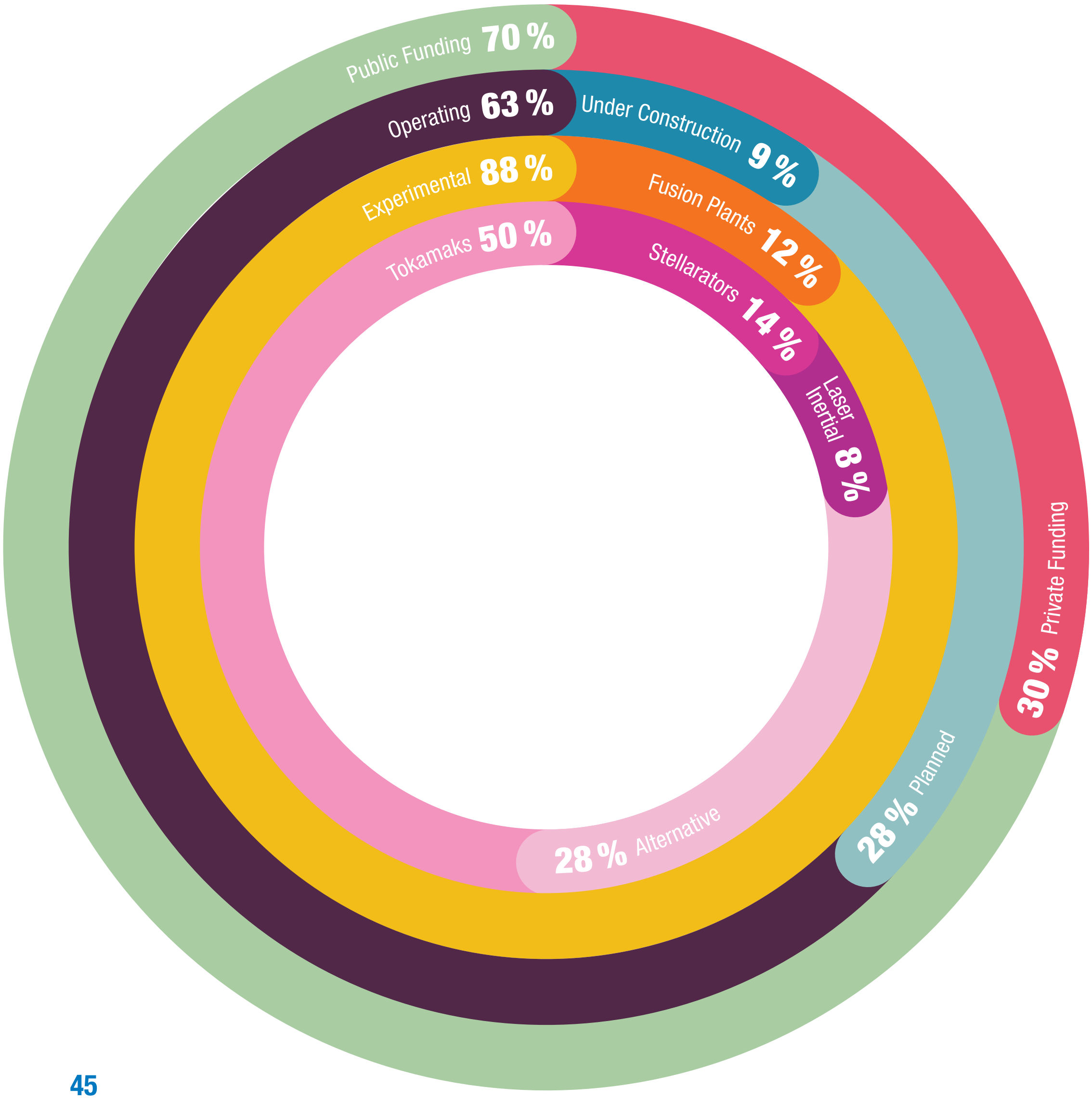
Member State	Funding (US $ billion)	Time frame
Germany	~1.4	over 5 years
Korea, Rep.	~0.9	over 10 years
UK	~0.8	over 5 years
USA	~1.5[a]	per year

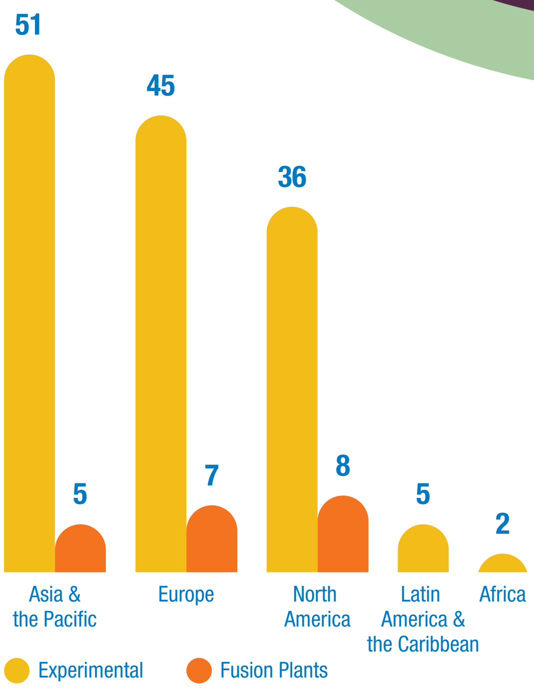
[a] This includes US $690 million from the US Department of Energy's National Nuclear Security Administration to support inertial confinement fusion for missions of the National Nuclear Security Administration and not for fusion energy development.

Key programmes implementing industry led fusion development models

Some of the world's biggest fusion players are implementing their own models to involve the industry and advance fusion energy development.

- China's Fusion Consortium: Comprises central government owned enterprises and research institutes, including some of the nation's largest energy and steel firms.
- Germany's Funding Initiative: Combines efforts from companies, universities and research institutions to construct a fusion power plant in Germany by 2040.
- Italy's DTT Consortium: Composed of many Italian research institutions, government and regional partners, and international stakeholders.
- Japan's Research and Development Moonshot Programme: Encourages participation by private enterprises, universities and organizations to pursue multiple approaches to fusion energy.
- Republic of Korea's new initiative: Aims to advance fusion plant technology through a PPP and establish a private led industrial fusion energy ecosystem.
- UK's Fusion Futures Programme: Aims to foster innovation and stimulate general industry capacity through international collaboration and the development of future fusion power plants, providing additional funding to develop infrastructure for private fusion energy companies.
- USA's Milestone-Based Fusion Development Program and Public–private Consortium Framework: Supports companies by providing funding based on the achievement and verification of pre-established commercialization milestones. The US Department of Energy also began gathering information on a proposed fusion energy public–private consortium. ■





The range of fusion devices, their operating status and funding in 2024 [22].

Number of fusion devices operating, under construction or being planned per region.

Fusion Device Information System

Key enablers on the path to an industry led fusion energy ecosystem

Fusion companies need to receive equal support in the energy market's political economy to drive commercialization and to scale up effectively. Other commercialized energy sources benefit from government partnerships, stable regulations and strategic fiscal incentives designed for public good [23]. Offering similar support to fusion energy developments could create a comprehensive pathway to commercial fusion. With supportive policies, governments can expedite the introduction of clean, abundant, efficient and secure fusion energy into the market.

In the USA, for example, tax policies have incentivized various clean energy technologies. The Inflation Reduction Act of 2022 extended many of these credits to the fusion energy sector [24] and starting in 2025, new "technology neutral" [25] tax credits will make commercial fusion energy production eligible. In the UK, the Government began amending regulations to classify fusion power plants as nationally significant infrastructure projects in England and Wales. This change will expedite planning applications by focusing on specific local issues rather than the necessity of the technology [26]. The EU's Net Zero Industrial Act also qualifies fusion as a "strategic technology" [27].

Beyond tax incentives, governments have created programmes to support clean energy technologies, such as renewable portfolio standards and mandates for carbon capture technology. Fusion energy, with its emission benefits and additional advantages, could, once operational, be included in these definitions of 'clean' or 'zero emission' energy. Resilient supply chains, effective regulatory frameworks and stable long term investment are essential if fusion is to be deployed at scale successfully. The development of a strong fusion industry calls for collaboration between governments, research and development organizations and private companies. ■

World Fusion Energy Group

To enhance collaboration across the fusion sector, the IAEA announced the establishment of the World Fusion Energy Group (WFEG) [28]. The WFEG aims to unite scientists, engineers, policy makers, financiers, regulators and private companies to accelerate the commercialization of fusion energy [13]. International cooperation and coordination has a vital role to play in the commercial rollout of fusion energy. The WFEG aims to bring together public and private sectors, industry, academia and civil society to form a cohesive global fusion community. By fostering a unified collaborative approach, the WFEG seeks to expedite the transition of fusion energy from development stages to commercial viability, ensuring that fusion becomes a bedrock of the world's clean energy future.

The WFEG will act as a catalyst at this critical juncture, where unified efforts are essential to rapidly advance fusion energy development, by focusing on:

- Increasing global cooperation, particularly through coordinating and providing space and recurring opportunity for interactive dialogue, exchange, planning and partnerships between stakeholders from industry, governments, academia, regulators and the public;
- Helping ensure efficacy of fusion energy research and development programmes such as in the use of existing facilities and planning for new facilities;
- Communally identifying existing technology and engineering gaps and developing strategies for establishing solutions at international level;
- Fostering discussion on establishing effective fusion regulation;
- Raising public engagement, enhancing youth involvement and increasing gender equality in fusion energy;
- Promoting integration of fusion into the energy market;
- Facilitating the integration of fusion into the existing energy systems, including the support infrastructure. ■

The IAEA will actively support the advancement of commitments made in the framework of the WFEG. In collaboration with its Member States and other partners, the IAEA will periodically organize gatherings of the group to review progress towards these outcomes, ensure high level political engagement and promote further collaborative action on fusion energy. Through these efforts, the IAEA aims to facilitate continuous progress and cooperation in the global pursuit of fusion energy development.

IAEA Director General Rafael Mariano Grossi and Italian Prime Minister Giorgia Meloni will co-chair the inaugural ministerial meeting of the WFEG (courtesy of the Government of Italy).

The first Ministerial Meeting of the WFEG

Fusion pathways

An overview of national strategies, international agreements, private and equity investments and regulatory processes that come together to advance the commercialization of fusion energy.

National strategies and international agreements

During the 29th IAEA Fusion Energy Conference, the UK unveiled its fusion energy strategy [29], introducing the new Fusion Futures Programme. This initiative will see an additional £650 million (US $793 million) invested over five years in a package of research and development programmes. The investment includes the creation of 2200 training places, a new fuel cycle testing facility and funding to develop infrastructure for private fusion energy companies, particularly at the UKAEA's Culham campus. This announcement followed the UK's decision to leave the Euratom Research and Training Programme.

Later in 2024 the UK Government announced an industry competition [30] to identify engineering and construction partners for the UK's prototype fusion energy plant, STEP. The competition aims to establish a public–private alliance led by UK Industrial Fusion Solutions, a subsidiary of the UKAEA, to deliver the STEP prototype. The project, located in the north of England, seeks to demonstrate net energy from fusion by the 2040s, with contracts for engineering and construction partners expected to be awarded by late 2025 or early 2026.

The UK Government also announced plans to streamline the planning process for future fusion plants. The UK Department for Energy Security and Net Zero began amending regulations to classify fusion power plants as nationally significant infrastructure projects in England and Wales. This change will expedite planning applications by focusing on specific local issues rather than the necessity of the technology. A consultation [26] will gather input on the national policy statement before it is presented for parliamentary approval.

Additionally, the UK Department for Energy Security and Net Zero and the US Department of Energy announced a new strategic partnership [31] aimed at accelerating the demonstration and commercialization of fusion energy, focusing on advancing their national fusion energy

UK Towards Fusion Energy 2023

US Fusion Energy Strategy 2024

strategies. Following this, the White House released a strategy for International Partnerships in a New Era of Fusion Energy Development [32] at the 28th United Nations Climate Change Conference (COP28), signalling the expansion of their vision to hasten fusion energy demonstration and commercialization, which was furthered by another partnership between the USA and Japan announced in April 2024 [33].■

The US Department of Energy announced its Fusion Energy Strategy 2024 [34], which aims to: (i) close the science and technology gaps to a commercially relevant fusion pilot plant; (ii) prepare the path to sustainable, equitable commercial fusion deployment; and (iii) build and leverage external partnerships. Closely coordinated with this strategy, the US Department of Energy also announced a US $180 million funding opportunity for Fusion Innovative Research Engine Collaboratives and released a new vision for its Fusion Energy Sciences programme entitled Building Bridges, which focuses on aggressively closing the science and technology gaps to a commercially relevant fusion pilot while supporting foundational research in fusion energy sciences and enabling technologies.

1 The opening ceremony of the 29th IAEA Fusion Energy Conference in London. From left: A. Bowie, the UK Parliamentary Under Secretary of State for Nuclear and Networks; IAEA Director General Rafael Mariano Grossi; and Sir Ian Chapman, Chief Executive Officer of the UKAEA.

2 IAEA Director General Rafael Mariano Grossi at COP28 in Dubai, United Arab Emirates, in December 2023.

IAEA's Fusion Energy Discussion at COP28

In 2024 the US Government significantly increased funding for fusion energy research, allocating US $790 million to the US Department of Energy's Office of Fusion Energy Sciences. In addition, inertial confinement fusion received US $690 million through the National Nuclear Security Administration's budget. This was further supplemented by a US $42 million programme aimed at advancing foundational inertial fusion energy science and technology, known as Inertial Fusion Energy Science and Technology Accelerated Research. Altogether, the US $1.58 billion [35] in funding represents a record investment from the US Government in fusion energy and inertial confinement fusion. Additionally, the Government proposed expanding tax credits to support a broader range of clean energy technologies, including fusion energy under the 2022 Inflation Reduction Act [36].

In the dynamic landscape of fusion energy, PPPs are increasingly taking shape. The US Department of Energy announced agreements to provide US $46 million in funding to eight companies for the first 18 months of aiming to advance designs and research and development for fusion power plants, as part of its Milestone-Based Fusion Development Program. These companies were selected from numerous applicants who submitted proposals outlining their plans to bring commercial fusion energy to market. The funding will be disbursed based on the achievement and verification of pre-established commercialization milestones by the US Department of Energy. Looking to the future, the US Department of Energy also began gathering information on a proposed fusion energy public–private consortium [37]. This consortium aims to amplify federal funding by integrating contributions from state and local governments, private sector investments and philanthropic sources.

Japan is following a similar trajectory. In 2023 the country adopted its first national strategy on fusion energy [38], emphasizing the creation of a domestic fusion energy industry with broader private sector involvement in research and development. This strategy included the establishment of the Japan Fusion Energy Council to foster related industries and develop guidelines for fusion energy technology regulation. Additionally a dedicated working group on fusion regulation was formed. In 2024 the Japanese Government announced a new research and development programme for fusion as part of its Moonshot Research and Development Program [39], further reinforcing its commitment to advancing fusion technology. The Government also plans to prioritize fusion energy education within academic institutions, ensuring that the next generation of scientists and engineers is well prepared to contribute to the field. These efforts are complemented by the strategic partnership with the USA to accelerate fusion energy development.

IAEA's Plasma Physics and Technology Aspects of the Deuterium–Tritium Fuel Cycle for Fusion Energy

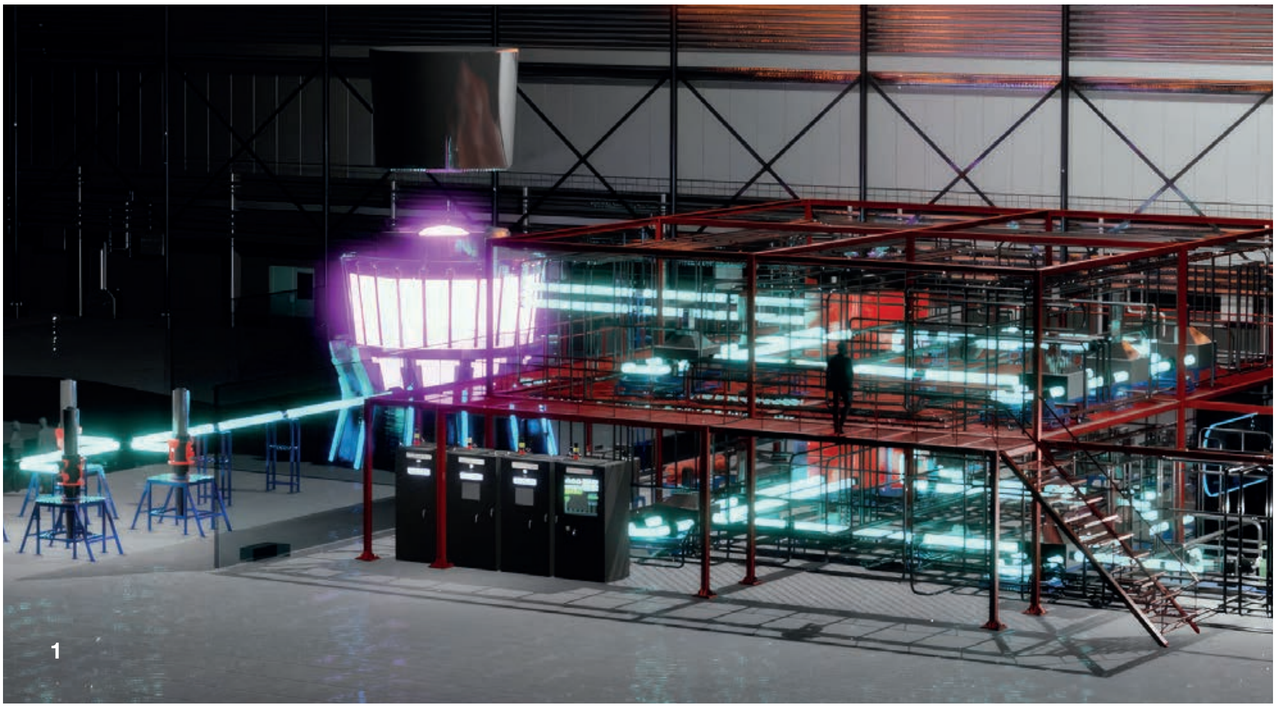
China is rapidly expanding its fusion energy programme, with increasing investment annually [40]. This vision is underscored by the formation of a consortium dedicated to fusion energy development led by China National Nuclear Corporation. This initiative focuses on high temperature superconductors, large capacity energy storage and tritium production. The consortium comprises 25 central Government owned enterprises and research institutes, including some of the nation's largest energy and steel firms. The Government announced the establishment of a new national company to spearhead the industry's development [41].

In July 2024 the Government of the Republic of Korea announced a substantial investment of 1.2 trillion won (approximately US $900 million) in fusion energy development. This initiative, scheduled to commence in 2026 and continue over a decade, aims to advance fusion plant technology through a PPP. The plan includes building a pilot plant with a power generation capacity of 100 MW in the 2030s with operations expected to start in the 2040s. The overarching goal is to establish a private led industrial fusion energy ecosystem [42].

Taking steps towards a comprehensive EU fusion strategy, the European Commission organized the EU Blueprint for Fusion Energy conference [43]. The event highlighted several key priorities for the EU: the need for enhanced collaboration, increased financing, regulatory certainty and the development of a skilled workforce.

As a prime mover in the EU, Germany's Federal Ministry of Education and Research announced that it will provide more than €1 billion for fusion research by 2028 in addition to the €370 million (US $396 million) allocated to research institutions.

This institutional funding was further reinforced by a new project funding programme named Fusion 2024 [44]. This programme aims to advance the technologies, components and materials needed for fusion power plants, focusing on both magnetic confinement and laser fusion. The first phase of Fusion 2024, set to be completed by the early 2030s, targets technological advancements, while the second phase will focus on integrating these technologies into a functional power plant design. The programme emphasizes application oriented collaborative research as a form of PPP aiming to accelerate the path to commercial fusion energy.



1 Illustration of UNITY-1, a non-radiological blanket component and thermal cycle test and user facility at Kyoto Fusioneering's Kyoto Research Centre in Japan. Early operations have begun while full scale testing campaigns are expected to commence in 2026 (courtesy of Kyoto Fusioneering, Japan).

2 USA's Deputy Secretary of Energy D.M. Turk and Japan's Minister of Education, Sports, Science and Technology, M. Moriyama, announcing their strategic partnership on advancing fusion energy (courtesy of the US Department of Energy, USA).

G7 Summit 2024 (courtesy of the European Union).

In Italy the Ministry of Environment has established the National Platform for Sustainable Nuclear Energy [45] with the primary objective of developing guidelines and a roadmap to track and coordinate the advancement of new nuclear technologies in the medium and long term. This includes exploring the potential for fusion energy to support the goal of achieving total decarbonization by 2050. The platform will involve a wide range of stakeholders, including public administration, businesses, trade associations, universities, research institutions and civil society.

Under the Italian G7 Presidency, fusion energy was highlighted with the G7 calling for international collaboration to accelerate the development and commercialization of fusion technology. This effort underscores the need for robust safety regulations, international supply chains and workforce development. The G7 committed to promoting collaborations, encouraging investment and establishing working groups to share best practices, welcoming the involvement of the IAEA and its Member States [46].■

In 2024 Canada and the UK signed an agreement [47] to work more closely together on the development of fusion energy, in areas including research, regulatory harmonization and improving skills in the workforce. The two countries will cooperate to support the deployment of fusion worldwide. Although Canada has not announced a formal national fusion programme, in 2024 Canadian Nuclear Laboratories (CNL) unveiled a report entitled Fusion Energy for Canada [48], which serves as a preliminary strategy and roadmap. The report calls on the Canadian Government to promptly mobilize a fusion ecosystem through a clear policy and mandate. The aim is for Canada to become an international leader in fusion technologies and services with the goal of demonstrating and adopting fusion energy between the 2030s and 2040s and deploying commercial fusion energy in Canada by 2050.■

In line with this vision, CNL signed a collaboration agreement with the UKAEA to develop technologies for tritium processing [49]. CNL also signed agreements and projects with Stellarex [50] and General Fusion [51], including the formation of the Fusion Fuel Cycle with

Fusion Industry Association: Commercializing Fusion Energy

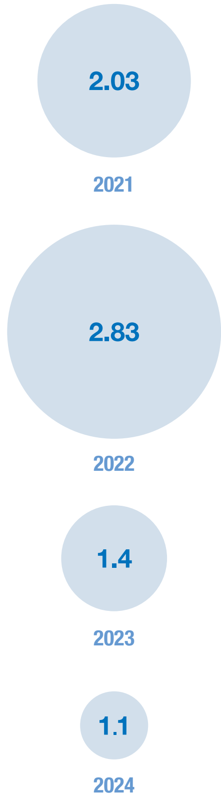
Kyoto Fusioneering [52], to build and operate UNITY-2, a tritium fuel cycle test and user facility. Scheduled to be commissioned by the end of 2025 and fully operational by mid-2026, UNITY-2 aims to support the integrated development of the deuterium–tritium fuel cycle from fuel discharge to purification and supply, demonstrating efficient tritium processing technology under relevant conditions and at relevant rates.■

Growing private and equity investments

The fusion energy industry is experiencing consistent year on year investment growth. While the majority of investments (~70%) have historically been directed towards fusion companies in the USA, 2023 marked a notable expansion in equity investments to fusion companies across a broader range of countries [53]. These countries include Canada, China, France, Germany, Israel, Japan and Sweden, reflecting a global surge in interest and funding for fusion energy development.

The annual fusion industry report released by the Fusion Industry Association, entitled The Global Fusion Industry in 2024 [15], which is the fourth such report, revealed that the fusion energy industry has now attracted a total of US $7.3 billion in investment, up from US $6.2 billion in 2023. The report surveyed 45 private fusion energy companies, ranging from established companies to new entrants. Although the USA continues to lead the field, with 25 active fusion energy companies (including many of the largest), the industry is becoming more geographically diverse, with at least one fusion energy company in 13 countries, with China, Germany, Japan and the UK each hosting three companies.■

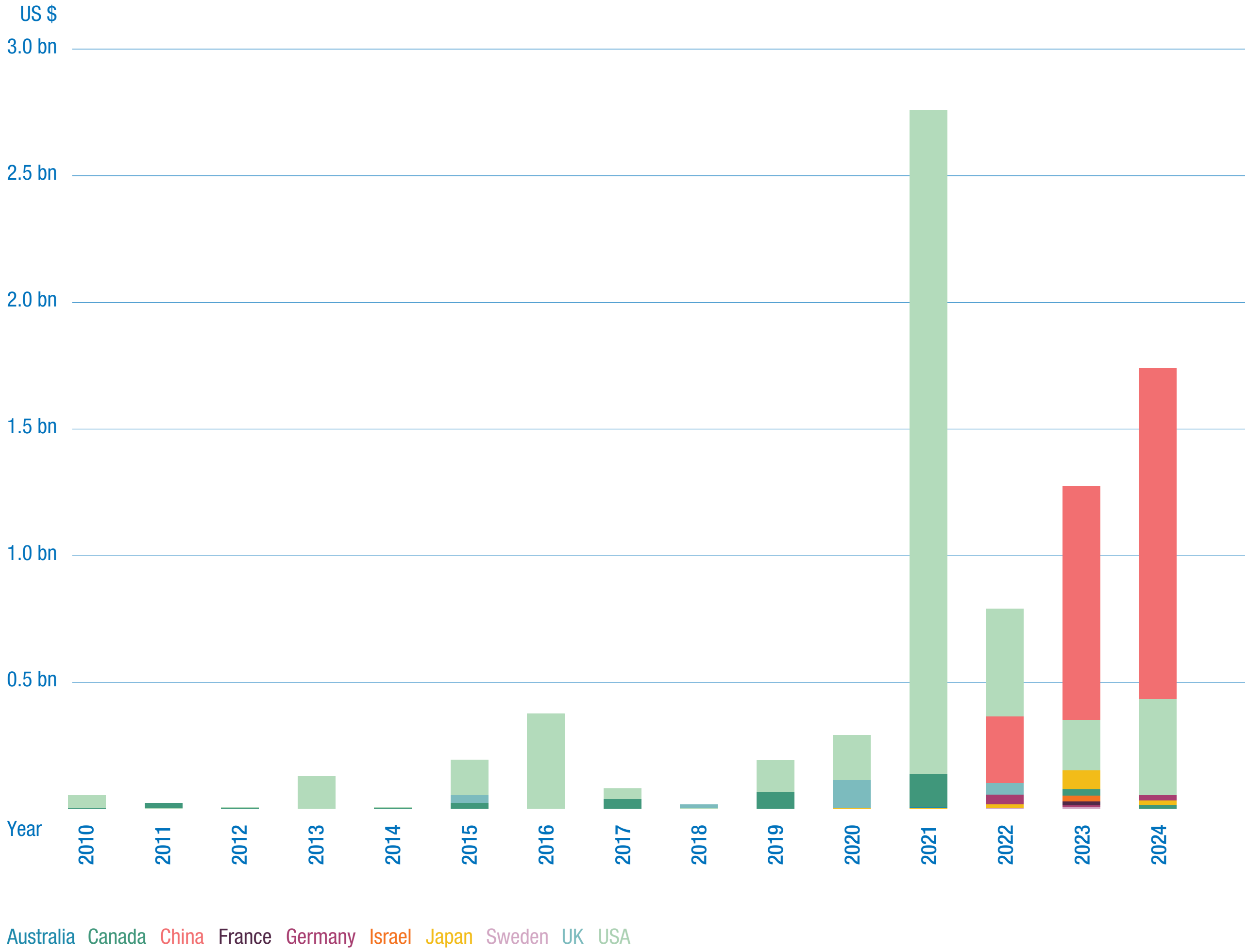
Declared funding by the Fusion Industry Association (in US $ billion)



Fusion Industry Association: The Global Fusion Industry in 2024

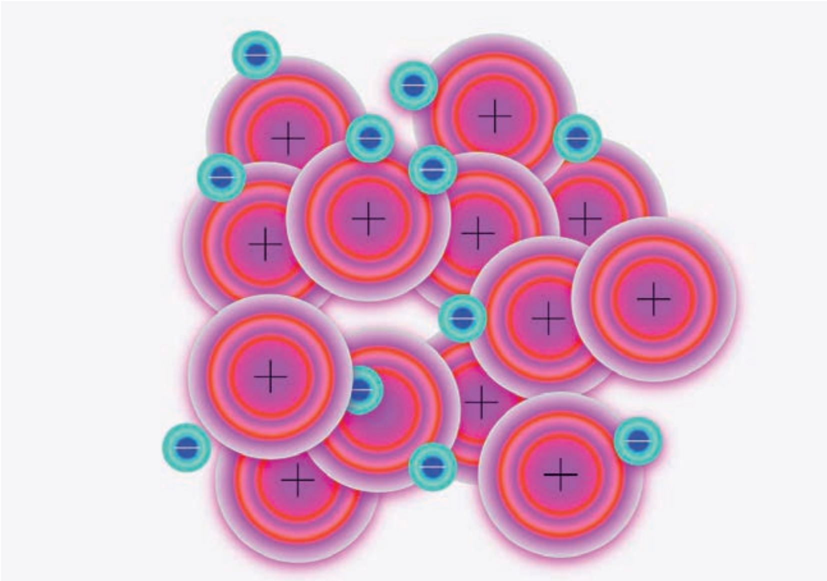
Apulia G7 Leaders' Communiqué

Equity investments to fusion energy companies between 2010 and 2024 by Member State [54]



Fusion Energy Base

Establishing regulatory approaches



Regulatory bodies and lawmakers are increasingly addressing the challenges and opportunities of fusion energy. In July 2024, US President Biden signed into law the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2023 or the ADVANCE Act of 2023 [55], which incorporates provisions from the bipartisan Fusion Energy Act [56]. This legislation aims to facilitate the development of commercial fusion energy by providing clear regulatory authority and incentives for investment. These provisions support the Nuclear Regulatory Commission's earlier decision to separate fusion energy regulation from that of fission energy, regulating near term fusion energy systems under the by-product material framework, similar to particle accelerators. In 2023, California became the first state in the United States to recognize fusion energy as a separate and distinct technology from fission energy. The Nuclear Regulatory Commission is in the process of drafting licensing guidance for fusion systems [57].

The UK Government confirmed that all planned prototype fusion energy facilities in the UK would continue to be regulated by the Environment Agency and the Health and Safety Executive, unlike nuclear power plants, which are regulated by the Office for Nuclear Regulation.

In addition, the Agile Nations working group on fusion energy, which comprises Canada, Japan and the UK as members, with Bahrain and Singapore as observers, produced joint recommendations [58] that recognize the important contribution that fusion energy could make to the global challenges of climate change and energy security. The policy paper also highlights the benefits of a harmonized approach to fusion energy regulation being adopted by several countries; and that advocate clarity on a regulatory framework that would apply to fusion energy facilities independent of the fusion technology and that maintains appropriate protections for people and the environment, proportionate to the hazards of fusion energy, while remaining transparent and pro-innovation.

Germany is following a similar path. A public hearing of the Committee on Education, Research and Technology Assessment held in 2024 highlighted the need for a pragmatic, innovation friendly and independent legal framework for fusion energy [59]. Such a framework aims to encourage private investment and support development of markets for fusion technologies.

Illustration courtesy of Ana Kova, USA.

Out looks

An analysis of trends in specific sectors and a breakdown of fusion energy in different regions around the world

Sectoral outlooks

A summary of the main examples of fusion developers and end users who work together to advance the commercialization of fusion energy

Oil and gas industries

Citing the need to diversify their portfolios amid global efforts to phase out unabated fossil fuels to achieve net zero by 2050, oil and gas industries have been making significant investments in fusion energy companies. Besides Chevron and Shell, fossil fuel majors investing in fusion energy firms also include Occidental, Eni and the Norwegian oil refiner Equinor [60].

TAE Technologies, a California based startup, is exploring using its fusion energy technology to power direct air capture facilities being developed by Oxy Low Carbon Ventures, a subsidiary of oil company Occidental. The companies signed a memorandum of understanding in June 2024 to seek opportunities to commercialize TAE Technologies' fusion technology to provide emission free power and heat for direct air capture devices. Established in 1998, TAE Technologies boasts of US $1.2 billion in investment from firms including technology giant Google, the investment bank Goldman Sachs and oil companies Shell and Chevron [61]. The company aims to have a grid connected fusion plant by the early 2030s.

While still unproven, direct air capture is seen by some experts as likely to be vital for achieving net zero by removing CO_2 from the air and undoing decades of damage to the atmosphere. But to be technically and economically viable, direct air capture would need a continuous source of affordable, zero emission energy of the type that fusion could provide.

In addition to investing in TAE Technologies, Shell, Chevron and Equinor have invested in Zap Energy. Zap Energy, based in Seattle, USA, aims to have its first grid connected fusion plant deployed within a decade.

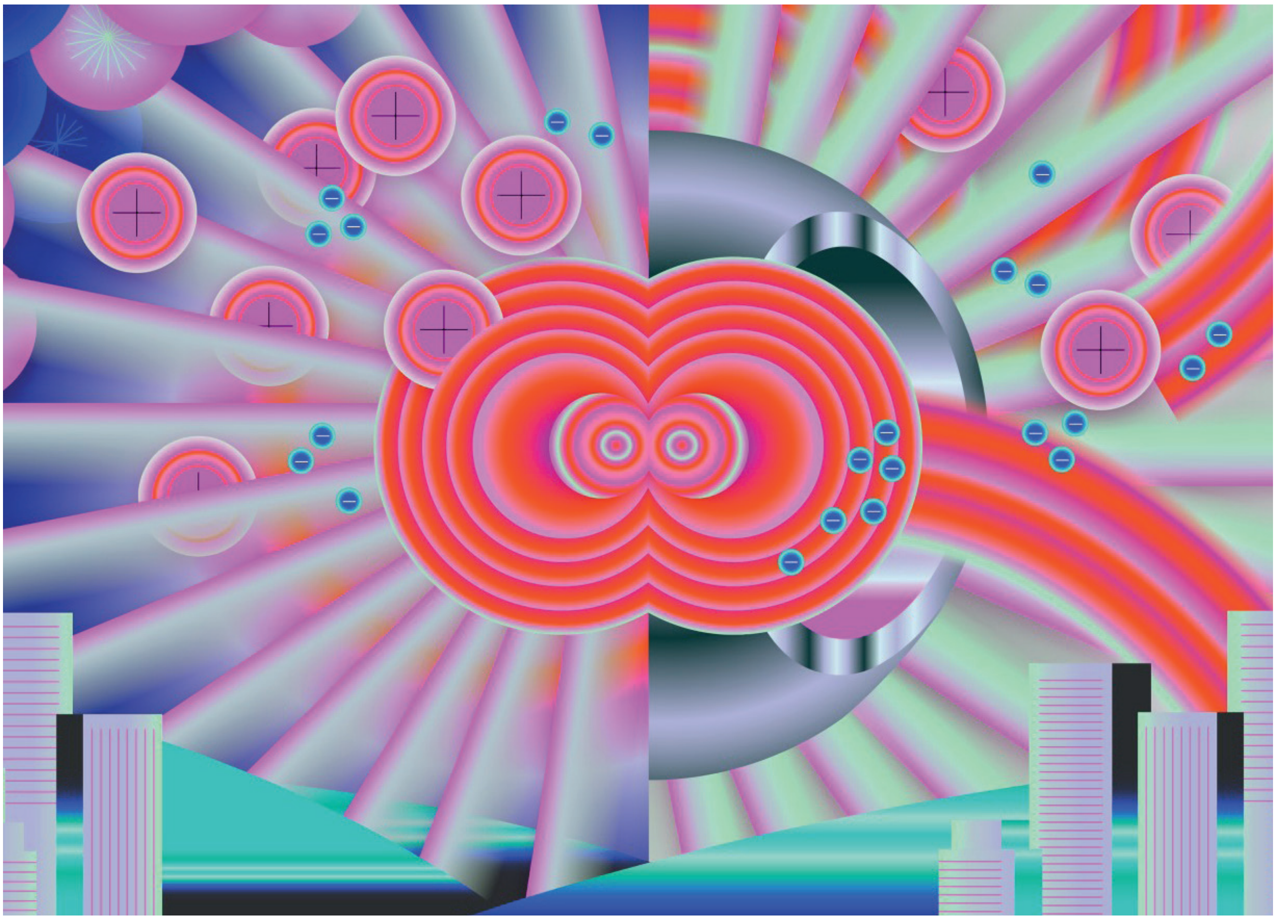
Eni, Equinor and Shell have invested in CFS. In 2023 Eni and CFS signed a collaboration agreement to support the industrialization of CFS technology. CFS's fusion plant is projected to be operational in the early 2030s. CFS has secured US $2 billion in investment so far. Eni also has a 25% stake in Italy's DTT facility under development near Rome, which is focused on research including solutions for extracting heat generated by the fusion process [62].■

Technology sector

Global technology companies have openly expressed their desire to use fusion energy to meet the skyrocketing power demands of their data centres, which support their fast developing AI systems. Sam Altman, CEO of OpenAI, was quoted in January 2024 as saying the future development of AI will need nothing short of the kind of major "breakthrough" that fusion energy can provide [63].

Altman himself has reportedly invested upwards of US $375 million in Helion Energy, a fusion technology developer based in the USA that also counts LinkedIn co-founder Reid Hoffman, eBay founder Peter Thiel and Facebook co-founder Dustin Moskovitz among its investors. Microsoft, an investor in OpenAI, is looking at fusion among other clean energy sources as it seeks to become CO_2 negative by 2030.

Microsoft signed an agreement in March 2023 to purchase electricity from Helion Energy's first fusion energy plant, which is currently planned to come online in 2028 with an output of 50 MW(e). Helion Energy, which boasts a total of US $0.6 billion



in investment, is reportedly working on its seventh prototype machine, which the company says will demonstrate the ability to produce electricity [64].

Bill Gates, the co-founder of Microsoft, and Jeff Bezos, the founder of online retailer Amazon, have been major investors in fusion energy startups including through Gates's fund Breakthrough Energy Ventures, which also includes contributions from UK businessman Richard Branson, media mogul Michael Bloomberg and Jack Ma, co-founder of Chinese online retailer Alibaba. In 2019, the fund together with other investors placed an initial US $115 million investment in CFS [65]. The commercial interest in fusion from Bezos goes back to at least 2011, when he joined a group that invested some US $20 million in Canadian fusion startup General Fusion, which now boasts a total of US $0.3 billion in investment and is developing magnetized target fusion. ■

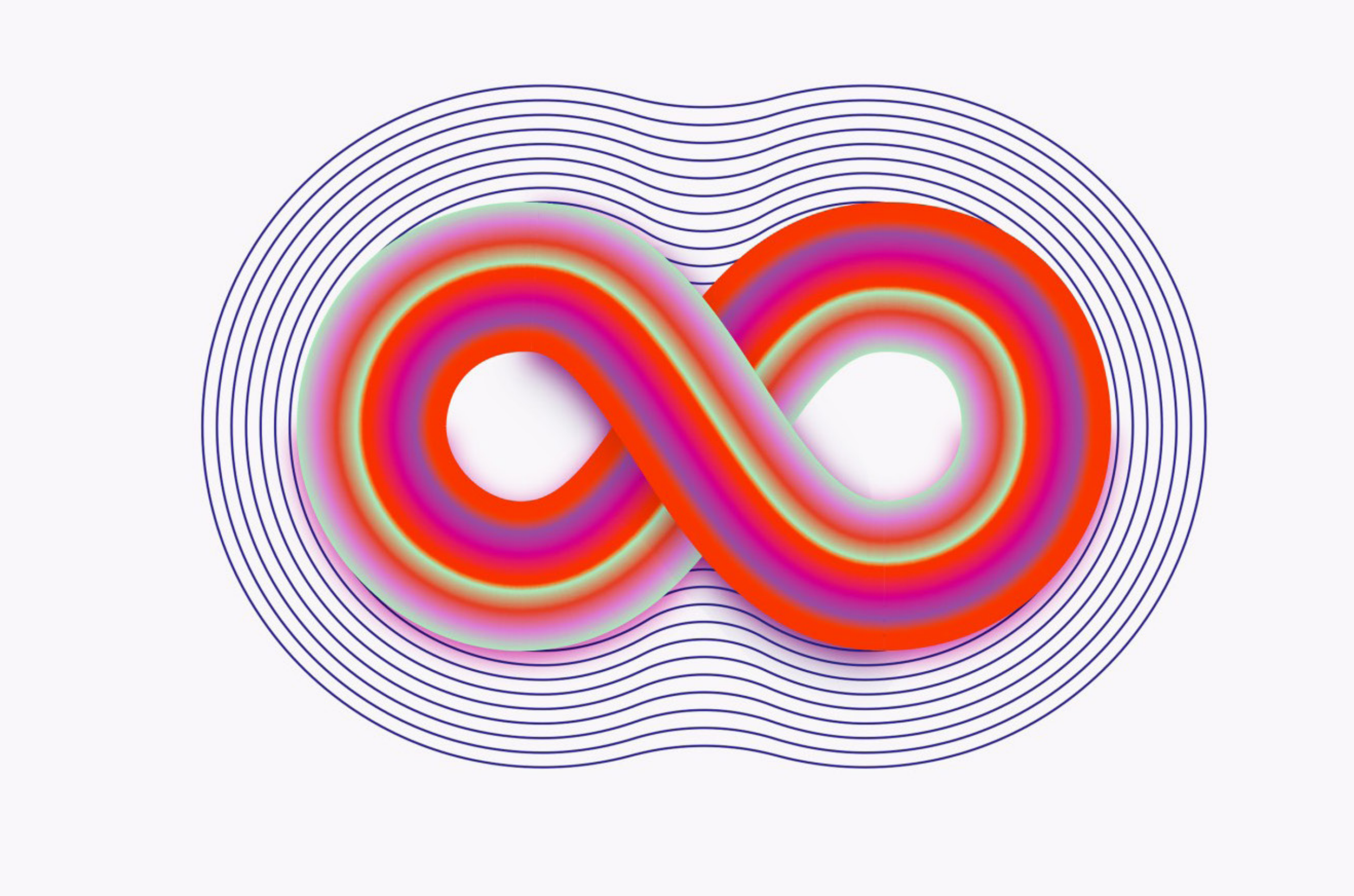
Electric vehicle industry

Israeli fusion startup nT-Tao, backed by Japan's Honda Motor, stated in January 2024 that it plans to develop mini fusion power plants for use as charging stations for electric vehicles, with the aim to commercialize the technology in the 2030s.

Each charging station would have an output of 10 000 to 20 000 kW and would be small enough to fit into a cargo container, according to the company, which has so far raised US $28 million in funding from investors including Japan's Mitsui Sumitomo Insurance Company and Honda Motor [66]. The car maker sees fusion energy as a potential game-changer for electric vehicles [67].

In China, electric vehicle maker Nio purchased a 20% stake in fusion technology startup Neo Fusion, which is 50% controlled by government owned companies and investment bodies in the province of Anhui. The startup, which boasts the equivalent of more than US $700 million in registered capital, will conduct research and development with the aim to commercialize fusion technology globally within two decades [68]. ■

Illustration courtesy of Ana Kova, USA.



Supply chains

The ITER project has laid a robust foundation for the establishment of a global supply chain for fusion energy. Each of the ITER members' respective agencies has its own contracts with companies and research and development organizations, providing in-kind contributions through a wide range of procurement arrangements. These agencies supply everything from vacuum vessel sectors to gyrotrons and high voltage power supplies, creating a supply chain now accessible to the emerging private fusion sector.

According to the Fusion Industry Association [69], spending by fusion energy companies on supply chain expenses increased to over US $612 million in 2023, up from approximately US $489 million in 2022.

These figures, based on a survey of companies, are likely conservative as not all companies responded. The largest expenditures were for specialized, non-fusion specific items such as vacuum pumps, along with raw materials, contract engineering and fuels. Companies anticipate spending 24% more on the supply chain in 2024 compared to 2023, with 77% of companies investing in expanding capacity to support the fusion industry.

In one example of increasing supply chain activity, UK based fusion company Tokamak Energy and Japan's Sumitomo Corporation agreed in July 2023 to cooperate on scaling up commercial fusion energy in Japan and around the world. Under the agreement, the Sumitomo Corporation will lend its expertise and investment to joint projects with Tokamak Energy, which are aimed at strengthening the global fusion supply chain. The Sumitomo Corporation is aiming to become a global leader in financing, construction and operating fusion power plants, while Tokamak Energy seeks to accelerate the commercialization and industrialization of its spherical tokamak devices in the late 2030s [70]. Tokamak Energy has secured US $0.3 billion in investment so far.

The UK based company, which is also developing HTS magnet

Illustration courtesy of Ana Kova, USA.

technology for applications beyond fusion energy, stated in January 2023 that it had signed an agreement with Japan's Furukawa Electric to supply hundreds of kilometres of HTS tape for its prototype fusion device. The HTS tape has been developed and supplied by Furukawa Electric, with its production under way at a site in New York, USA [71].

Nucor Corporation, North America's largest steelmaker and steel recycler, signed an agreement with Helion Energy in 2023 to build a 500 MW(e) fusion power plant at a Nucor steel manufacturing facility in the USA. According to the company, this is the first fusion energy agreement of this scale and is expected to pave the way for global decarbonization in industrial manufacturing [72].

Longview Fusion Energy Systems aims to scale laser based inertial confinement fusion for commercial power. The company contracted Fluor Corporation in April 2024 to design and build a modular power plant using advanced, efficient lasers and AI optimization. The initial plant design will deliver 1 GW to 1.6 GW of energy, with an initial 440 MW(e) plant set to be designed by 2027 and operational by 2032. Key challenges include managing radioactive tritium and adapting fusion generated steam to the grid. Longview Fusion Energy Systems is considering various locations, including repurposing coal plants to preserve jobs and infrastructure.

Meanwhile, the UKAEA and Research Centre Řež, a Czech research organization, signed a multi-year agreement in May 2024 to test HTS tapes for the UK's STEP prototype fusion plant. They will develop a unique test rig to study the impact of fusion relevant neutron spectra on HTS tapes, which will confine plasma at temperatures up to 150 million degrees Celsius. The rig, expected to be operational in 2026, will provide data on HTS tape durability, thereby aiding in the design and lifespan of STEP's HTS magnets.■

Utilities

USA based utility firm Constellation Energy, which already operates 21 nuclear reactors across the country and is aiming to become CO_2 neutral by 2030, will manage power marketing and transmission for Helion Energy's first fusion power plant [73], which is planned to come online in 2028 and provide electricity for Microsoft.

Ontario Power Generation, one of Canada's largest electric utilities, is also looking to contribute to the deployment of a fusion plant. In June 2024 the company announced it had signed a memorandum of understanding to explore the development and deployment of fusion energy in the province of Ontario with Stellarex [74], a US based fusion company. Ontario Power Generation and Stellarex said they will explore establishing a centre of excellence for fusion energy and identify potential future siting and deployment of a stellarator fusion plant in Ontario.

Another Canadian utility company, Bruce Power, announced in 2022 that it had signed an agreement with General Fusion and Canada's Nuclear Innovation Institute to collaborate on facilitating the deployment of fusion power in Ontario. With nuclear energy already providing almost two-thirds of electricity production in the province, the three organizations stated they will look to build on the region's existing clean energy technologies, skills and expertise. With a focus on stakeholder engagement, they said they would seek to raise awareness among residents, businesses and industries of fusion energy's potential to transform clean energy generation in Ontario [75].

Anhui Province Energy Group Company Limited, a major utility firm in China, has been reported to have invested in the fusion company Neo Fusion [76].■

Regional outlooks

Africa

Algeria, Egypt, Libya, Morocco and Tunisia

In Africa, research and development focused specifically on fusion energy is currently limited. However the region has expertise and skilled professionals in various fusion relevant fields. Plasma science research related to fusion is pursued by individual scientists and groups across multiple countries. For example Algeria, Egypt, Libya, Morocco and Tunisia are making steps towards education in the field of plasma science. Their universities are actively engaged in research, with a focus on areas such as radiofrequency plasmas and their application, materials science, plasma chemistry, plasma theory and modelling, among others. In addition, Egypt and Libya also host two tokamaks, further enhancing their contributions to the global scientific community. These initiatives highlight Africa's growing engagement in education and research in plasma science and fusion science.■

Asia and the Pacific

Australia and New Zealand

In Australia, fusion research is coordinated by the Australian ITER Forum, a network of scientists and engineers from various disciplines. The research efforts are concentrated on plasma diagnostics, plasma theory and modelling and materials studies for fusion applications. Australia also hosts HB11 Energy, a private fusion company focusing laser driven fusion.

In New Zealand, private company Openstar Technologies has raised US $12 million for developing fusion technologies based on the levitated dipole approach.■

China

China hosts more than a dozen fusion experimental devices, either in operation, under construction or planned. These efforts are supported by state owned industrial firms, universities and research institutes. Key fusion machines like EAST and HL-3 have achieved excellent experimental results and China is building on these successes by investing in subsequent fusion projects, including BEST and CFETR, paving the way to fusion plant deployment. Additionally, the country is focusing on developing a fusion specific workforce, with a goal of training 1000 new plasma physicists. China is also building a research facility called Comprehensive Research Facility for Fusion Technology, known as CRAFT, which serves as a platform for developing and testing fusion energy plant components. It is expected to be finished in 2025 [77].

Several companies are also heavily investing in fusion research with numerous planned projects [78]. In 2024 the government announced a new national company [79] with ambitious plans to construct a pilot engineering research plant, currently in the conceptual design phase. This plant aims to achieve 300 MW of fusion power in steady state operation and 600 MW in pulsed operation, with flexibility for adjustments during the design phase. Construction is planned to start by 2030, with all hardware expected by 2035. To support this effort, the HL-3 tokamak is being upgraded to enable deuterium–tritium experiments. The deuterium–tritium upgrade is expected to be completed by 2027, although the commencement of deuterium–tritium operations will depend on the licensing and commissioning of the device.■

India

India's primary focus in fusion and plasma research, development, funding and contributions is centred around the ITER project. The country operates several experimental research devices and is in the process of outlining its fusion roadmap for the next 25 years, which includes plans for two new machines ahead of the Indian DEMO launch in the late 2040s. The first machine would be a fusion neutron source based on a spherical tokamak, while the second would be a conventional tokamak designed for steady state operation, roughly two-thirds the size of ITER.■

Islamic Republic of Iran

The Islamic Republic of Iran currently operates three tokamaks, Alvand, Damavand and IR-T15, dedicated to studying plasmas under different experimental conditions.■

Israel

Since 2019 Israel has been home to the private fusion company nT-Tao. This company has disclosed US $32 million in funding and is actively developing stellarator technology for energy production.■

Japan

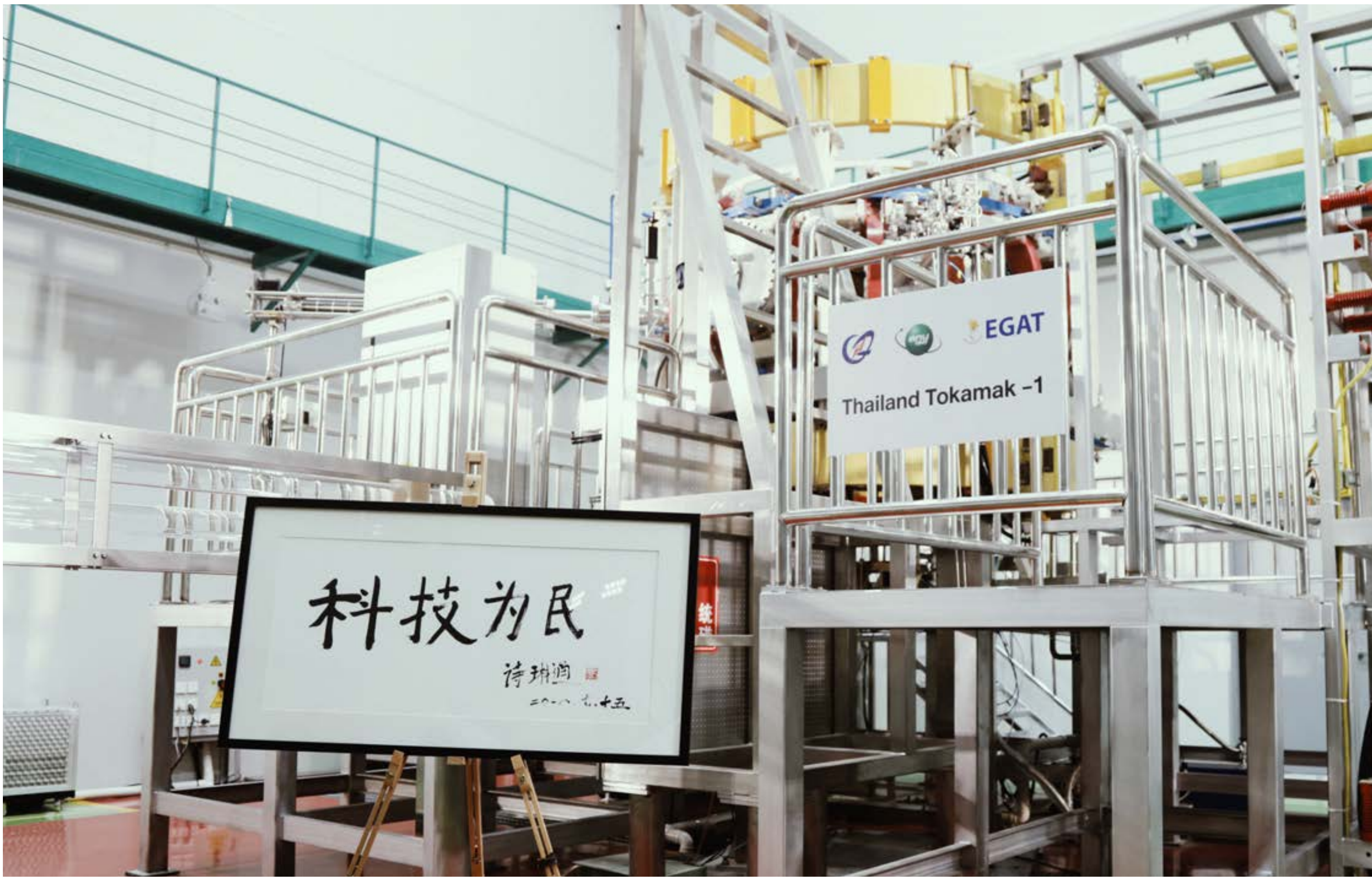
Operating more than 20 experimental fusion devices, Japan is at the forefront of advancing fusion research and development. The Japanese fusion strategy envisions a phased approach towards the practical application of fusion energy. The phases include the JA DEMO concept design and elemental technology development until 2025, engineering design and full scale technology development from 2025 to 2035 and a decision on transitioning to JA DEMO construction after 2035, informed by progress on the ITER project.

Additionally, the bilateral collaboration between Japan and the EU through the Broader Approach agreement focuses on (i) plant design and research and development, (ii) a project[2] for engineering validation and design for fusion material irradiation facilities and (iii) the exploitation of JT-60SA, which started operating at the end of 2023. Various academic research efforts are also ongoing at universities and specialized institutes, utilizing research devices and high power laser facilities.■

[2] The goal of this project, also called the IFMIF Engineering Validation and Engineering Design Activities (IFMIF/EVEDA), is to provide proof of concept for the IFMIF DEMO Oriented Neutron Source (IFMIF–DONES) under construction in Spain. As part of the IFMIF/EVEDA activities, three prototype facilities were constructed to validate each one of the three key components of IFMIF-DONES. The test facility, located in Karlsruhe, Germany, tests concepts for IFMIF-DONES's high flux test module. The lithium target facility, located in Ōarai, Japan, tests concepts for IFMIF-DONES's lithium liquid curtain. Finally, the accelerator facility, located in Rokkasho, Japan, tests concepts for IFMIF-DONES's deuteron beam particle accelerator.

▲

Rendering of an aerial view of the Comprehensive Research Facility for Fusion Technologyin Hefei, Anhui Province, China (courtesy of Hefei Institutes of Physical Science of the Chinese Academy of Sciences, China).



Lebanon

In Lebanon, academic research is dedicated to advancing crucial aspects of fusion science, including plasma turbulence, confinement, diagnostics development and divertor concepts.■

Pakistan

Pakistan currently operates two tokamaks, GLAST-III and MT-I, with a third, MT-2, under construction and a fourth, PST, in the planning stages [80]. This concerted effort aims to enhance Pakistan's capabilities in fusion energy.■

Republic of Korea

The Republic of Korea is forging ahead with a fusion roadmap aiming to construct its demonstration fusion plant by 2050. The Korean roadmap for K-DEMO involves conceptual design activities running up to 2030, followed by engineering design from 2031 to 2035. These efforts are supported by cutting edge research and development at the KSTAR and VEST tokamaks, laying the groundwork for the essential science and technology needed by 2035. Additionally in the Republic of Korea, a new project entitled the Korea Fusion Engineering Advanced Test complex is under consideration. This facility is designed to meet the requirements for fusion plant breeding blanket performance evaluation, including continuous long term operation, high fusion neutron flux and a large target size to irradiate the tritium breeding unit [81]. The complex will feature:

- An integrated breeding test facility, harnessing a 40 MeV deuteron accelerator driven system with a maximum of 10 mA for fusion like neutron generation, pivotal for testing blanket components;
- A blanket system test facility, crafted to demonstrate the reliability and safety of the blanket and its ancillary systems;
- A fuel cycle pilot facility, designed to verify continuous fuel cycle operation using H_2/D_2 at a 1:10 pilot scale.■

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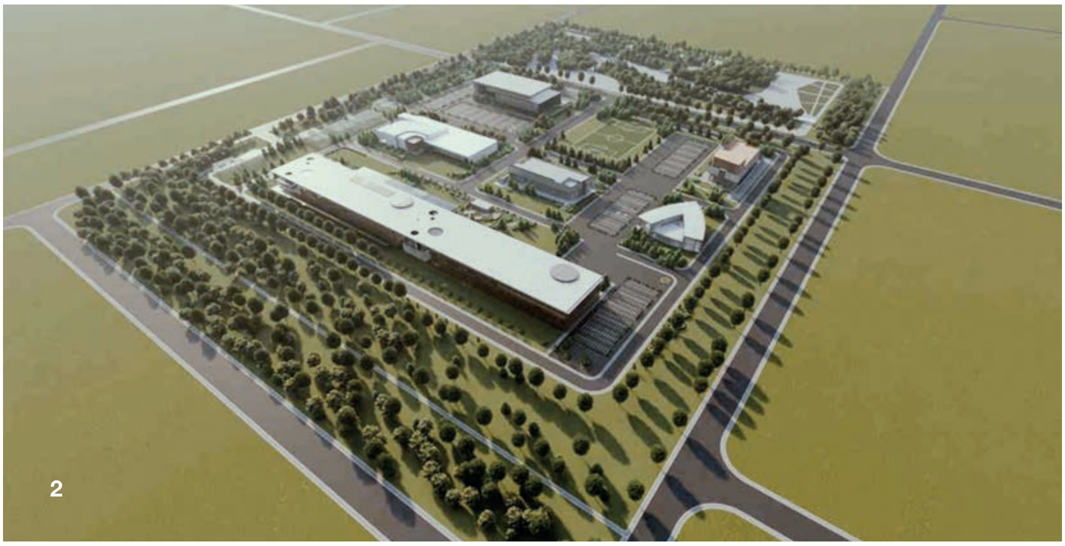

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Saudi Arabia

Saudi Arabia is investing in research and development for advanced energy technologies, including fusion. As part of this strategy, the JIMCO Technology Fund has invested in General Fusion and CFS.■

Singapore

Temasek Holdings Limited, a Singaporean investment firm owned by the Government of Singapore, has been reported to have invested in CFS [82].■

Thailand

In 2023 Thailand, in cooperation with China, switched on its first tokamak, TT-1 [83]. As the first tokamak in Southeast Asia, TT-1 is a fundamental facility for advancing fusion research in Thailand and neighbouring countries. It promises to be an invaluable learning tool for fusion plasma and engineering development [84].■

Several countries are spearheading an initiative that envisions the creation of the Arab Fusion Energy Agency, which will serve as a central hub to coordinate fusion research and collaborations within the region, secure funding for future fusion energy projects and ensure active participation of these countries in global fusion energy efforts.

1 TT-1 officially launched in Thailand (courtesy of Hefei Institutes of Physical Science, Chinese Academy of Sciences, China).

2 A rendering of the proposed Korea Fusion Engineering Advanced Test complex (courtesy of the Korea Institute of Fusion Energy, Republic of Korea).

View into the plasma vessel of W7-X (courtesy of
Max Planck Institute for Plasma Physics, Germany).

Europe

EUROfusion, FuseNet, Fusion for Energy and IFMIF-DONES

EUROfusion is the European research and development consortium[3] established for coordinating and funding fusion research and development across Europe. The EUROfusion roadmap follows a milestone approach, setting goals over the short, medium and long term [85]. Initially, the roadmap focuses on contributing to the ITER project. Subsequently, attention shifts to EU-DEMO, which is expected to start operating by 2050.

The short term goals emphasize research, development and construction of ITER and material testing facilities such as IFMIF-DONES, along with proceeding with the conceptual design of EU-DEMO. In the medium term, the focus shifts to the scientific and technological exploitation of ITER and IFMIF-DONES and commencing the engineering design phase of EU-DEMO with industrial involvement. The long term vision includes the design, construction and operation of EU-DEMO, alongside intensified industry collaboration.■

FuseNet is the European fusion education network, serving as the central hub for fusion education through its educational development and mobility programmes. As an organization affiliated to EUROfusion, FuseNet is tasked with progressing and coordinating educational activities that support the EUROfusion roadmap. FuseNet's initiatives include funding schemes for Master's students, networking activities for doctoral students, the development of educational materials and the organization of events for younger educational levels. Additionally, FuseNet works to strengthen relationships with industry, ensuring that educational efforts align with the needs and advancements within the fusion sector.■

Fusion for Energy is the EU organization managing Europe's contribution to ITER. Europe is responsible for nearly half of the project, while the other six members (China, Japan, India, the Republic of Korea, the Russian Federation and the USA) contribute equally to the rest. Fusion for Energy works together with European industry and research organizations to develop and manufacture the high technology components that Europe will provide to ITER.■

In recent years, several private companies in France, Germany, Italy and Sweden among others, have been engaging significantly in developing fusion technologies. To secure Europe's long term energy supply, ten European companies agreed in June 2024 to establish the European Fusion Association [86]. This unified body will bring together various stakeholders in the fusion industry and national governments, accelerating the industrialization of fusion energy.■

[3] The participating countries in EUROfusion are Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine and the UK.

1

Germany

Germany is a leader in several areas of fusion energy development, including stellarator research, tokamak physics, fusion technologies and materials and plasma–wall interactions. The W7-X reactor, located in Germany, is the world's largest stellarator. It features modular superconducting coils, enabling steady state plasma operation to explore power plant relevant regimes.

The German Government has been accelerating efforts towards fusion commercialization, recognizing the rise of private companies in the country and aiming to leverage their contributions and engagement. German companies active in the fusion energy sector have established the Pro-Fusion industry association [87]. This association will serve as an entry point to contribute to the development of the economic fusion ecosystem and, in the long term, shape public opinion on fusion energy.■

Italy

Italy has a vibrant fusion programme. The DTT facility is a new Italian fusion project expected to start operation after 2025. The DTT consortium is composed of many Italian research institutions, government and regional partners, international stakeholders and private firms and has raised nearly €500 million to construct the facility. Italy is also home to several experimental fusion research facilities and is actively involved in the preparation for ITER operations and designing the EU-DEMO. Italian industries have secured more than €1.8 billion in contracts for the development of fusion technologies.■

France

France hosts ITER and several other fusion research devices, including the WEST tokamak and various laser facilities. Additionally the startup Renaissance Fusion — which is developing a stellarator concept with HTS magnets and liquid walls — is based in France. To support research and development in this area, the French Government is exploring frameworks to stimulate PPPs.■

Kazakhstan

Fusion research activities in Kazakhstan encompass a range of initiatives, from small test benches focusing on low temperature plasmas to full scale fusion research experiments like the KTM tokamak as well as accelerator applications

for fusion research. Kazakhstan has a cooperation agreement with ITER to study the radiation resistance of plasma diagnostics and the quality of structural materials. Additionally, Kazakhstan has partnered with Belarus, Kyrgyzstan, the Russian Federation and Tajikistan for the joint use of the KTM tokamak, further enhancing research and development efforts in the region.■

Russian Federation

In the Russian Federation the development of fusion energy is guided by the National Strategy for Atomic Energy, which focuses on pure fusion energy machines and fusion–fission hybrid reactors. Major participants in this initiative include the State Atomic Energy Corporation "Rosatom", the Ministry of Science and Higher Education (including the Russian Academy of Sciences) and the Kurchatov Institute, National Research Centre. Research efforts are concentrated on tokamaks, laser systems and fusion–fission hybrids. The latter are considered of strategic importance for the operation of future nuclear reactors and fusion plants in the Russian Federation.■

▲

1 IFMIF-DONES is a material testing facility under construction in Granada, Spain. Spain and Croatia are project leads, with Spain funding 50% of all construction costs and 10% of operating costs, with Croatia responsible for 5% of each. IFMIF-DONES will use a particle accelerator to produce a continuous wave deuteron beam aimed at a target made of a liquid lithium curtain. The interaction between deuterium and lithium will generate enough free neutrons to simulate the planned neutron flux over time of EU-DEMO. Directly behind the lithium target will be the high flux test module, which will house capsules of material samples for neutron irradiance testing [88].

2 IAEA Director General Rafael Mariano Grossi visiting the remote handling and robotics test facility at Culham, UK.

United Kingdom

The UKAEA is the UK's national organization responsible for the research and delivery of fusion energy. It oversees UK Industrial Fusion Solutions, which is responsible for delivering the STEP prototype fusion plant. Additionally, the UKAEA is implementing the UK's Fusion Futures Programme to support the UK Fusion Strategy. This programme includes establishing new facilities at the UKAEA's Culham Campus in the south of England to advance new technologies and expand fusion fuel cycle capabilities. The Fusion Futures Programme aims to foster world leading innovation and stimulate general industry capacity through international collaboration and the development of future fusion power plants. Additionally, a fusion skills package aims to be introduced to nurture expertise across a spectrum of disciplines and levels.

In 2021, the UKAEA opened its Fusion Technology Facility [89] near Rotherham in South Yorkshire to develop and test materials and components for future fusion power plants. The UKAEA also collaborates with academia, other research organizations and the industrial supply chain in various areas, including robotics and materials.

The UKAEA fusion machines include MAST Upgrade and the JET tokamaks. The JET concluded its plasma operations at the end of December 2023. the UKAEA is now overseeing JET's decommissioning and repurposing project [90]. The project is a world first programme that will contribute scientific and engineering knowledge to the development of future fusion machines and power plants. These activities include the robotic disassembly of JET's tokamak, research into the recovery of tritium for reuse as fusion fuel and further development at the UKAEA's Culham Campus.

1 IAEA Director General Rafael Mariano Grossi visiting the MAST Upgrade.

2 The agreement between the IAEA and the Government of Chile was signed by L. Huerta of the Chilean Nuclear Energy Commission and witnessed by Chile's Energy Undersecretary L. F. Ramos.

2

3

Latin America and the Caribbean

Argentina, Brazil, Chile, Costa Rica, Mexico and Peru

The worldwide trend of increasing fusion activities is observed in several Latin American countries, including Argentina, Brazil, Chile, Costa Rica, Mexico and Peru. To strengthen regional capabilities in fusion and plasma physics, efforts are focused on advancing research, establishing collaborations through joint experiments, research internships, coordinated programmes and summer schools dedicated to plasma physics and fusion science and technology.

In 2024 the IAEA, in collaboration with the Princeton Plasma Physics Laboratory, launched a new series of webinars to highlight current progress and developments in fusion and plasma science activities in Latin America.

In May 2024 the IAEA and the Government of Chile signed an agreement to strengthen cooperation on nuclear technology and lithium [91]. This agreement is aimed at harnessing nuclear technology to enhance lithium mining and paves the way for wider regional support from the IAEA. Lithium has applications in fusion and other energy sectors.

In June 2024 the IAEA and the Government of Peru signed a joined declaration on cooperation in the area of nuclear technology applications in the mining industry to help Peru protect the environment by enabling it to carry out mining and lithium exploration sustainably [92].■

3 IAEA Director General Rafael Mariano Grossi signing an agreement with Peru's Foreign Minister, J. González-Olaechea, during his visit to Peru in June 2024.

IAEA webinars on Fusion Activities in Latin America

North America

USA

The US Department of Energy has been investing in fusion research for decades through the Office of Science Fusion Energy Sciences programme. These efforts include support for international collaborations like ITER, as well as the National Nuclear Security Administration's Inertial Confinement Fusion programme. More recently, the Advanced Research Projects Agency–Energy (known as ARPA-E) has targeted potentially transformative areas of fusion research and development, focusing on enabling timely fusion commercialization. The US Department of Energy's fusion programme is now focusing on bridging fundamental fusion research with applied research to meet the needs of the growing US fusion industry. The USA hosts the highest number of fusion energy companies (25 in total), including many of the largest. Additionally, the USA hosts the highest number of fusion machines either in operation, under construction or under development (over 40). In this context, the US Department of Energy is now coordinating a broad set of new activities to support eventual fusion commercialization. These include the Milestone-Based Fusion Development Program [93], international engagements to strengthen energy security and technological leadership [94] and various interagency government efforts [95] to assess the international competitive landscape and market development, develop appropriate regulatory frameworks, build out supply chains, ensure inclusive workforce development, ensure energy and environmental justice, ensure viable waste disposition and recycling pathways and ensure public engagement.■

Canada

Canada has significant expertise in key areas essential for developing a mature fusion industry, such as deuterium and tritium production and handling, robotics, remote handling and materials science. These capabilities can be leveraged to support fusion development and align well with the needs of fusion technologies. Despite these strengths, government support for fusion research and development in

Canada is moderate, with current activities primarily driven by academic institutions and private companies.

The CNL-led Fusion Energy for Canada report [48] urges the Canadian Government to create a clear policy and mandate to mobilize a fusion ecosystem. In response, CNL announced it will open its small modular reactor Invitation Process to include fusion prototype plants [50]. CNL also expanded its Canadian Nuclear Research Initiative programme to focus more on fusion based research and development, fostering collaborative projects with advanced nuclear reactor vendors.■

IAEA Director General Rafael Mariano Grossi visiting the Princeton Plasma Physics Laboratory, USA, in September 2024.

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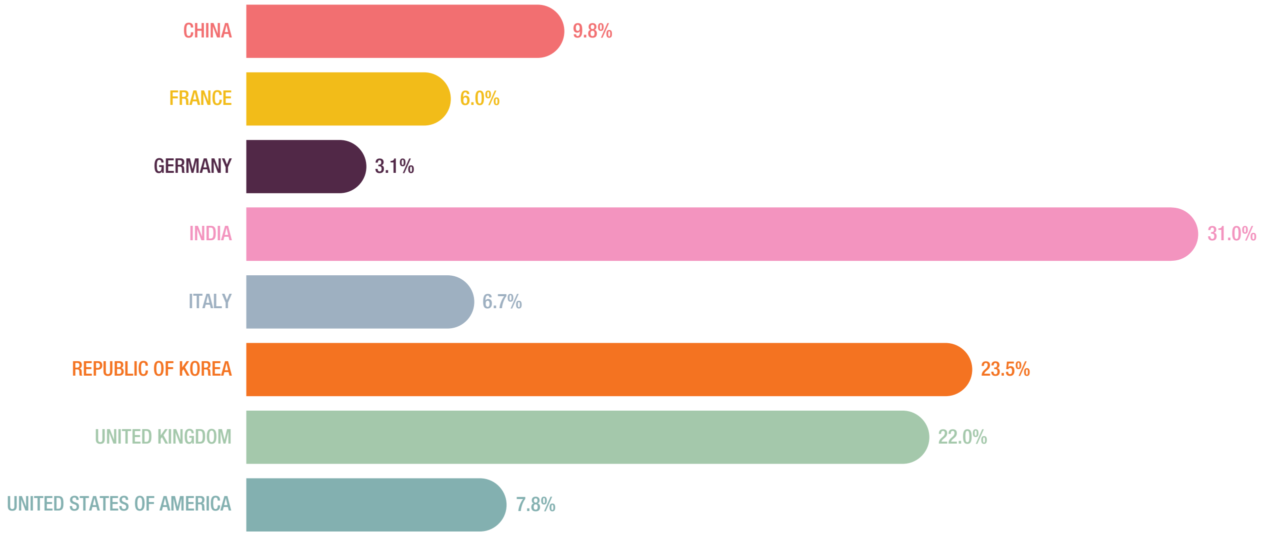


Positive compound growth rate of first authorship papers presented at the Fusion Energy Conference per country (2006–2023).
Over the past 17 years, India, the Republic of Korea and the UK have been the fastest rising countries in terms of the total number of first authorship papers, reflecting their growing engagement in international cooperation. This rise in contributions highlights the vital role of global collaboration in accelerating progress towards fusion energy, as shared expertise and collective efforts drive innovation and advance scientific breakthroughs.

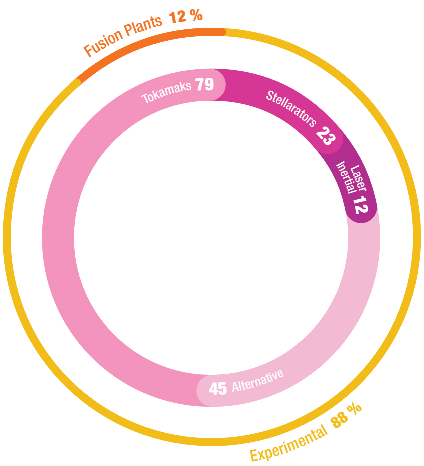
Fusion energy in 2024: A snapshot

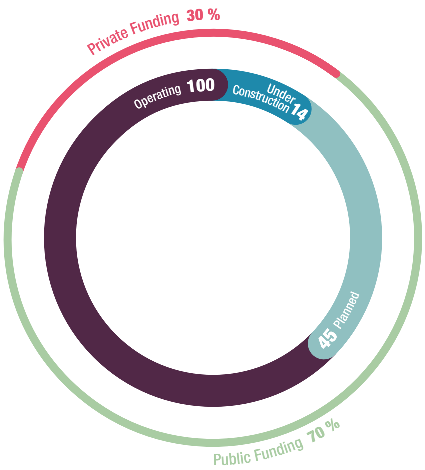
From 2021 to 2024, the fusion energy sector experienced significant growth and diversification. The total number of fusion projects surged, with a notable increase in alternative and inertial confinement and stellarator designs, highlighting a shift towards exploring varied technologies beyond traditional tokamaks.

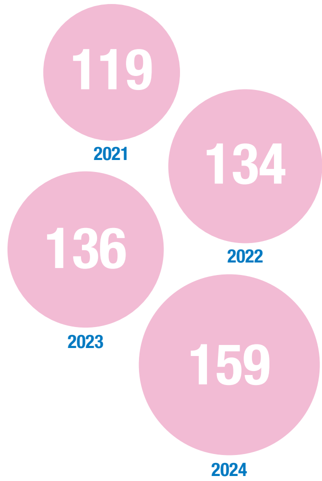
In 2024 there is a more equitable distribution between experimental projects and fusion plants, indicating a maturation of the field. The sector also saw a significant rise in planned projects, reflecting strategic long term planning. Additionally, private sector involvement nearly doubled, demonstrating increased commercial interest and investment, which complements continued strong public sector support. The year 2024 marks a dynamic phase in fusion energy, characterized by technological diversity, strategic planning and enhanced drive for public–private collaboration.■

Increased investment and a variety of technological approaches

The fusion energy sector's recent trends suggest a promising future characterized by accelerated technological advancement, increased investment and broader adoption. The diversification into alternative fusion designs and the significant rise in laser and stellarator projects indicate that various technological pathways are being explored to achieve sustainable fusion energy.





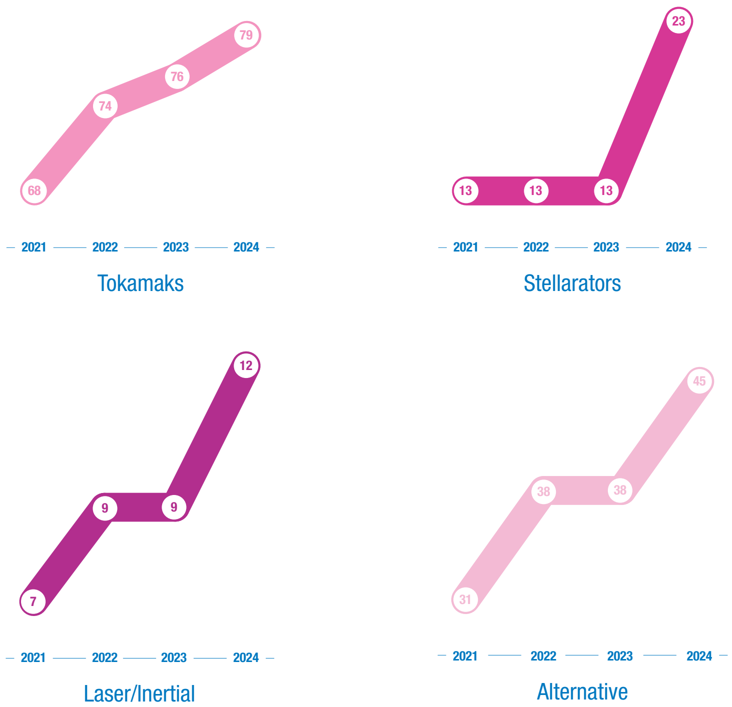


In 2024 the majority of fusion machines were experimental designs (139 devices). While tokamaks remain the prevalent device in 2024, other machine designs have grown in popularity in recent years.

Public funding for fusion machines remains steady in 2024, while private funding in fusion projects has more than doubled since 2021. There are more fusion machines in operation than ever before in 2024, with five more operating than 2023 and many more planned.

As the number of fusion energy projects grows year on year, so too does the expanding interest and investment in the fusion energy sector from public and private entities.

This diversified approach could significantly enhance the potential for breakthroughs. The continued collaboration between public and private sectors will be crucial in accelerating technological development and scaling up successful experimental models to operational fusion plants.■



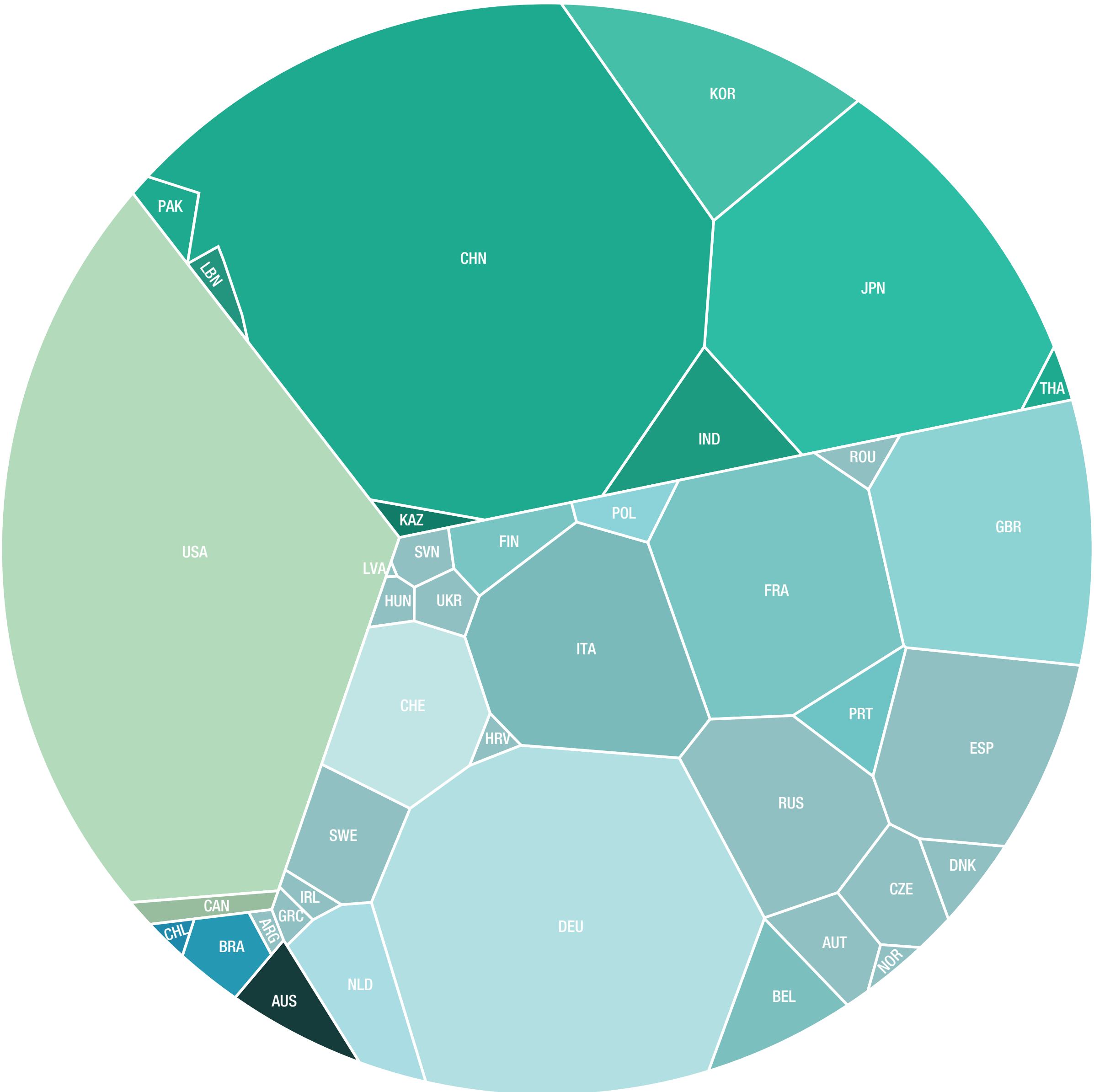
Number of fusion devices per year.

Trends in fusion energy research (2014–2023)

Fusion energy research has seen significant contributions from countries worldwide over the past decade. The cumulative number of accepted articles to the Nuclear Fusion journal between 2014 and 2023 highlights the growing interest and advancements in this field.

The trends observed here are a reflection of the data as they pertain directly to Nuclear Fusion content and are not necessarily reflective of the global trends in research and development in fusion.

With the largest number of contributions over the years is China (858 accepted articles). This underscores China's extensive focus on fusion over the past decade. Other countries including the USA (762 articles) and Germany (447 articles) are also making major contributions, driven by substantial investments in science and technology. Furthermore, countries such as Japan (346 articles), France (200 articles), the UK (196 articles), Italy (174 articles) and Spain (129 articles) also have longstanding research programmes and are critical players in international research. Along with China and Japan, another major contributor from Asia is the Republic of Korea (129 articles), further emphasizing this region's growing role in fusion research. India (57 articles) is also making notable strides in this domain. The Russian Federation (115 articles) maintains a strong presence in the fusion research landscape. Countries such as the Netherlands (47 articles), Sweden (43 articles), Belgium (38 articles), the Czech Republic (36 articles) and Australia (13 articles) have consistently maintained a steady influx of contributions, particularly through international partnerships and in specialized research areas of fusion energy.■



Most cited article published since 2014

Most downloaded article published in 2024

Most downloaded article published since 2014

Global trends in fusion energy research, indicated by the number of articles accepted for publication in the Nuclear Fusion journal (articles accepted in 2014–2023). ITER and JET contributions are reported with France and UK, respectively.

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ABBREVIATIONS

AI	artificial intelligence
CFETR	China Fusion Engineering Test Reactor
CFS	Commonwealth Fusion Systems
CNL	Canadian Nuclear Laboratories
DONES	DEMO Oriented Neutron Source
DTT	Divertor Tokamak Test
EU	European Union
EU-DEMO	European Demonstration Power Plant
EVEDA	engineering validation and engineering design activities
HTS	high temperature superconducting
IFMIF	International Fusion Materials Irradiation Facility
JET	Joint European Torus
KSTAR	Korea Superconducting Tokamak Advanced Research
NIF	National Ignition Facility
PPP	public–private partnership
UKAEA	United Kingdom Atomic Energy Authority
W7-X	Wendelstein 7-X
WFEG	World Fusion Energy Group

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“As we navigate the complexities of this groundbreaking technology, our resolve is steadfast: to harness the power of fusion energy for a sustainable, prosperous and peaceful world.”

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Rafael Mariano Grossi