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Fusion energy

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Abstract:

Fusion energy, a natural process that powers the Sun and sustains the planet's climatic and biological systems, has become a first-order scientific challenge and a key strategic asset in global geoeconomic competition. Replicating this mechanism on Earth requires highly demanding conditions from both a scientific and technological standpoint. This was achieved for the first time in 2022 at the National Ignition Facility in the United States.
Renewed interest in fusion responds to two structural dynamics: the progress of critical enabling technologies —advanced materials, superconductivity, artificial intelligence and high-performance computing— and the growing demand for firm, decarbonized and scalable energy to sustain highly electrified and digitalised economies.
In 2025, more than 50 private companies were engaged in the development of fusion technologies, with cumulative investment approaching 10 billion dollars since 2021. Strategic advantage will be determined by industrial leadership, advanced manufacturing capacity and the coherent integration of public policy, regulation, financing and human capital. Countries that succeed in translating scientific leadership into productive capacity will consolidate their position in the new global energy order.

Keywords:

Fusion energy, Energy transition, Energy sovereignty, Enabling technologies, Energy geopolitics, Technological competition.

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FUSION ENERGY

FUSION ENERGY IS NO LONGER JUST A MATTER OF ADVANCED PHYSICS, BUT A STRATEGIC VECTOR OF ECONOMIC, INDUSTRIAL AND TECHNOLOGICAL POWER, WHOSE EVOLUTION WILL HAVE MAJOR IMPLICATIONS FOR ENERGY GEOPOLITICS IN THE COMING DECADES.

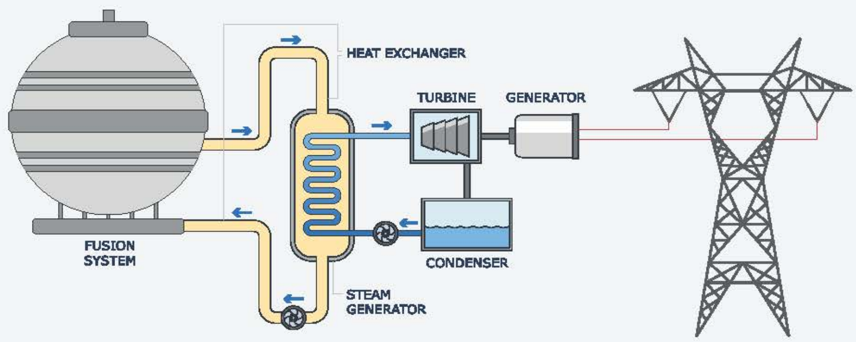


Fig. Simplified diagram of a fusion power plant. Source: Knowable Magazine.

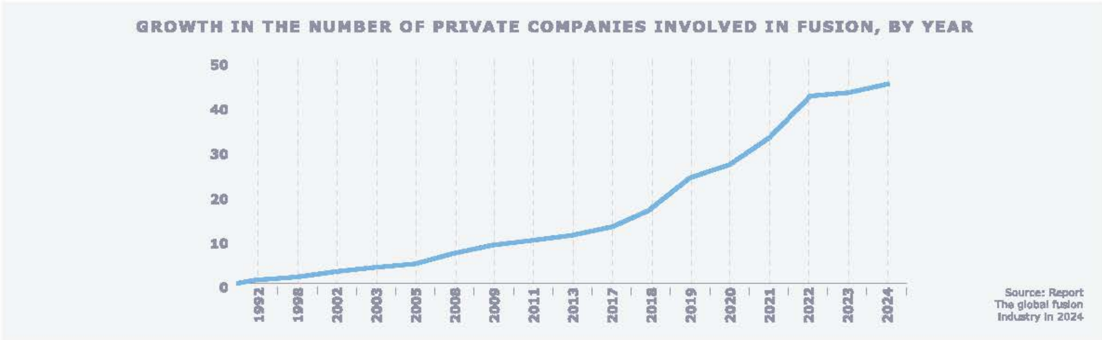
ADVANTAGES OF FUSION ENERGY

- **CLEAN AND EMISSION-FREE:** FUSION REACTIONS DO NOT PRODUCE CO_2 OR OTHER POLLUTANTS ASSOCIATED WITH THE COMBUSTION OF FOSSIL FUELS.
- **STABLE AND RELIABLE ENERGY:** PROVIDES CONTINUOUS AND STABLE ENERGY SUPPLY, 24 HOURS A DAY, COMPLEMENTING INTERMITTENT RENEWABLE ENERGIES SUCH AS SOLAR AND WIND POWER.
- **INTRINSIC SAFETY:** NO RISK OF CORE MELTING, GUARANTEEING A HIGH LEVEL OF OPERATIONAL SAFETY.
- **LOW-LEVEL WASTE:** GENERATES LOW-LEVEL, SHORT-LIFE RADIOACTIVE WASTE, WHICH SIMPLIFIES ITS MANAGEMENT.
- **FUEL ABUNDANCE:** DEUTERIUM, EXTRACTED FROM WATER, AND TRITIUM OFFER THE POTENTIAL FOR VIRTUALLY UNLIMITED RESOURCES.

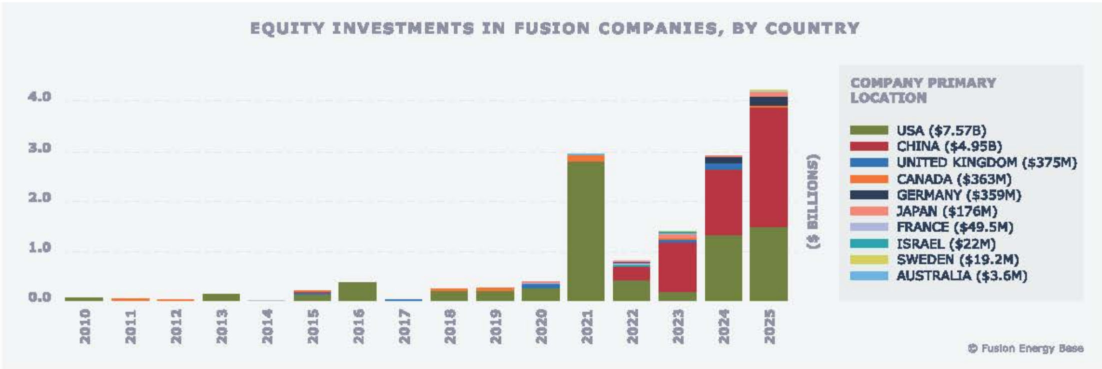
TWO STRUCTURAL FACTORS CONVERGE TO PLACE FUSION AT THE CENTRE OF THE CONTEMPORARY ENERGY DEBATE:

1. **ADVANCES IN ENABLING TECHNOLOGIES**
   -FROM NEW MATERIALS TO ADVANCED COMPUTING CAPABILITIES-
2. **GROWING NEED FOR RELIABLE, DECARBONISED AND SCALABLE ENERGY SOURCES**

THERE ARE MORE THAN 50 PRIVATE COMPANIES AROUND THE WORLD DEVELOPING VARIOUS FUSION CONCEPTS.



FINANCING OF PRIVATE INITIATIVES: WITH AN ANNUAL GROWTH OF 178% COMPARED TO THE PREVIOUS YEAR AND A TOTAL INVESTMENT OF NEARLY US $10 BILLION SINCE 2021.



DEADLINES FOR GRID CONNECTION

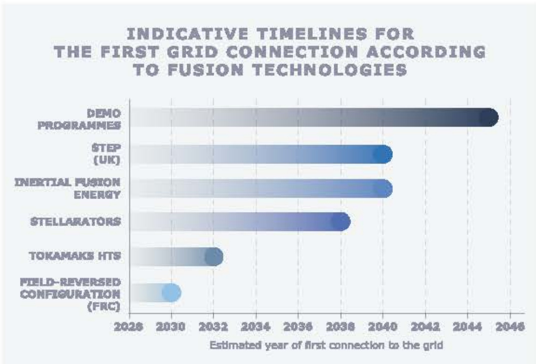
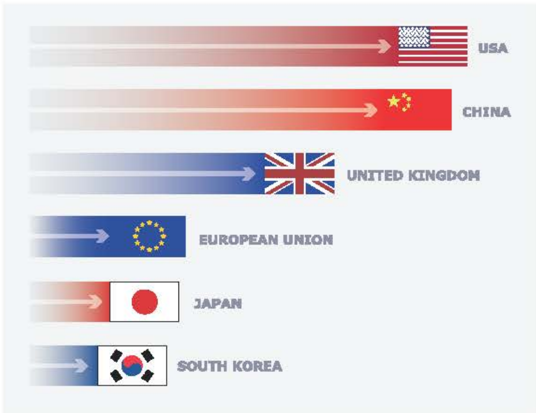


Fig. Indicative timelines for the first grid connection of the main fusion energy development lines.

THE GLOBAL RACE TOWARDS LEADERSHIP IN FUSION ENERGY



Introduction

Fusion energy is not an abstract promise or a theoretical construct: it is a physical phenomenon that occurs constantly in nature and constitutes the very basis of life on Earth. The solar radiation that sustains the planet's climatic, biological and economic systems is the direct result of fusion reactions in the core of the Sun. Reproducing this process in a controlled manner on Earth therefore represents one of the greatest technological challenges of modern history, but also one of the greatest strategic opportunities for the energy systems of the future.

The development of fusion energy requires an exceptional level of technological sophistication. For a fusion reaction to produce net energy, it is necessary to achieve what is known as plasma ignition: a state in which the fusion process becomes self-sustaining. Achieving this involves heating a plasma to temperatures of hundreds of millions of degrees Celsius, confining it using extremely intense magnetic fields, and maintaining these conditions long enough for the energy produced to exceed the energy invested. This milestone was achieved for the first time in December 2022 in an experiment at Lawrence Livermore National Laboratory, in the United States, marking a historic turning point in the scientific credibility of fusion as an energy source.

However, the renewed global interest in fusion cannot be explained solely by this experimental achievement. Two structural factors converge to place fusion at the centre of the contemporary energy debate. The first is the advancement of enabling technologies —from new materials to advanced computational capabilities— that significantly reduce the technical and economic barriers that have historically existed. The second is the growing need for firm, decarbonised and scalable sources of energy capable of complementing intermittent renewable energy and sustaining highly electrified economies without dependence on fossil fuels.

A paradigmatic example of this technological transformation is the development of high-temperature, high magnetic field superconducting magnets. These magnets make it possible to substantially increase the strength of the magnetic field, which in turn drastically reduces the size of the fusion devices needed to confine the plasma. This reduction in scale has direct implications for costs, construction times and industrial viability. While ITER —the world's largest fusion experiment— uses "traditional" superconducting coils that generate fields of around 5 tesla in a machine with a radius greater than 6.2 metres, new devices such as SPARC, developed by

Commonwealth Fusion Systems, use high-temperature, high-field superconductors capable of reaching 12 tesla (and tested up to 20 tesla) in a machine with an approximate radius of 1.85 metres. This difference is not merely technical: it reflects a paradigm shift that brings fusion closer from the realm of large-scale international science to that of industrial engineering and geoeconomic competition.

In this context, fusion energy ceases to be solely a matter of advanced physics and becomes a strategic vector of economic, industrial and technological power, whose evolution will have profound implications for the geopolitics of energy in the coming decades.

This chapter analyses fusion energy not only as a technological promise, but as an emerging factor in the transformation of the global energy system and of economic power relations between states. Unlike other chapters focused on mature technologies, this one addresses a technology still in a pre-industrial phase, but whose development trajectory is already influencing regulatory, industrial and strategic decisions at a global scale.

The chapter is structured into five major sections that connect technology, regulation, advanced computational capabilities and geopolitical competition, with the aim of showing how fusion may become a central element of the geoeconomics of energy in the coming decades, and how the race for control of this technology has already begun.

Fusion Energy: innovation, energy sovereignty and global competitiveness

Energy has always been a central pillar of geopolitics. Control over energy resources, technologies, and supply chains has shaped international relations, economic development, and national security for over a century. From coal and oil to natural gas and nuclear fission, each major energy transition has reconfigured global power balances, created new dependencies, and redefined strategic influence. In the context of the twenty-first century—marked by climate change, geopolitical fragmentation, and rapid technological acceleration—fusion is increasingly viewed not merely as a scientific ambition, but as a potential strategic asset with profound geopolitical implications.

Fusion energy occupies a unique position in the global energy landscape. Unlike fossil fuels, it promises near-zero operational carbon emissions; unlike renewable energy sources, it offers the prospect of continuous, dispatchable power independent of weather or geography; and unlike nuclear fission, it carries intrinsically different safety characteristics and long-term waste profiles. These features place fusion at the intersection of climate policy, energy security, industrial strategy, and technological sovereignty. As a result, fusion is emerging as a subject of strategic interest for governments before its commercial deployment.

By 2025, fusion has reached a critical inflection point. Decades of publicly funded research—epitomized by large international programmes such as ITER—have been complemented and increasingly challenged by a rapidly expanding private fusion sector. Scientific milestones, including sustained high-performance plasma operation, ignition-relevant results in inertial fusion, and advances in high-temperature superconductors, have shifted fusion from a distant promise to a pre-industrial technology under active strategic consideration[1] This transition fundamentally alters the way fusion must be understood within energy context: no longer solely as a long-term research endeavour, but as an emerging component of energy systems and industrial competition.

From a geostrategic perspective, fusion's most distinctive attribute is its potential to decouple energy production from traditional resource geopolitics. Fusion fuels—primarily isotopes of hydrogen—are widely available, with deuterium extractable from seawater and tritium potentially bred within fusion systems themselves. While tritium availability represents a near- and medium-term strategic constraint, the long-term vision of self-sustaining fuel cycles contrasts sharply with the geographically concentrated reserves of oil, gas, and critical minerals that dominate today's energy geopolitics. If realised at scale, fusion could significantly reduce exposure to fuel price volatility, supply disruptions, and coercive energy diplomacy 2.

At the same time, fusion introduces new strategic dependencies that differ from those of previous energy systems. Rather than fuel access, geopolitical advantage is likely to be determined by leadership in advanced manufacturing, materials science, superconducting technologies, digital control systems, and high-performance computing. In this sense, fusion aligns closely with broader strategic competition in deep technologies, where energy, digitalisation, artificial intelligence, and advanced materials increasingly converge. Countries that succeed in mastering these enabling

[1] National Academies of Sciences, Engineering, and Medicine. Bringing Fusion to the U.S. Grid. Washington, DC: The National Academies Press, 2021.
[2] World Energy Outlook 2023. IEA, París, 24 de octubre de 2023.

technologies—and in translating scientific leadership into industrial capability—stand to gain not only energy security, but also economic and technological influence. Leadership in fusion will depend not only on technical breakthroughs, but on the ability to integrate policy, regulation, finance, workforce, and industry into coherent national and regional strategies.

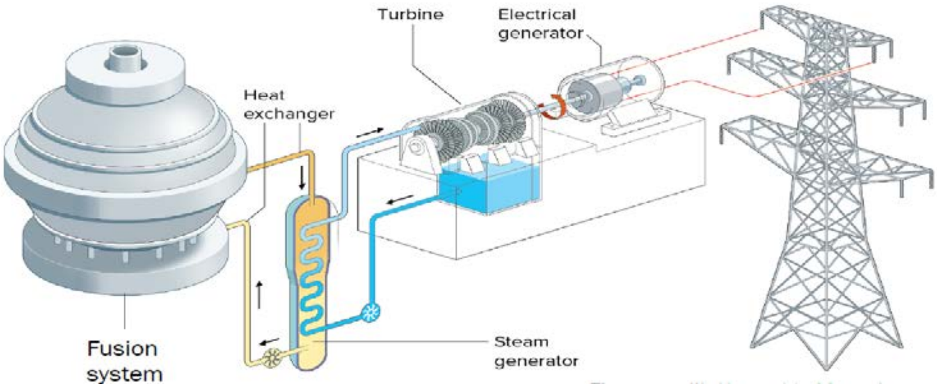


Figure 1.Simplified diagram of a fusion power plant. Source: Knowable Magazine.

The strategic relevance of fusion must also be understood within the context of global decarbonisation. As countries pursue net-zero commitments, limitations in existing energy technologies have become increasingly apparent. Variable renewables require large-scale storage and grid reinforcement; nuclear fission faces political, regulatory, and waste-related challenges in many regions; and carbon capture technologies remain uncertain at scale. Fusion is therefore increasingly framed by policymakers as a potential “firm, clean power” option capable of complementing renewables in future low-carbon systems [3] This framing elevates fusion from a scientific curiosity to a potential pillar of long-term climate and energy strategies.

Also, fusion energy has the potential to play a transformative role in meeting the rapidly expanding demand for electricity over the coming decades. As societies electrify transportation, industry, and buildings, and as new digital technologies—especially artificial intelligence (AI) and data centres—drive unprecedented increases in power consumption, energy systems will need significantly larger, reliable, and low-carbon

[3] European Commission (2023) – State of the Energy Union 2023.

baseload capacity. Global electricity demand is projected to continue rising strongly through mid-century, with scenarios indicating that total demand may increase by more than the equivalent of adding a country the size of Japan's consumption each year through the late 2020s, driven by electrification and digital growth[4]. Growth in electricity consumption could more than double between 2023 and 2050 as electrification expands into new sectors, with emerging demand centres such as AI and cloud computing significantly shaping future load patterns, including forecasts of data centre demand doubling by 2030 to nearly 1 000 TWh per year due to AI and related technologies[5]. By providing firm power that can operate around the clock without the variability of wind or solar, fusion could help ensure grid stability and support the energy system backbone required to satisfy the growing global appetite for firm sources of electricity.

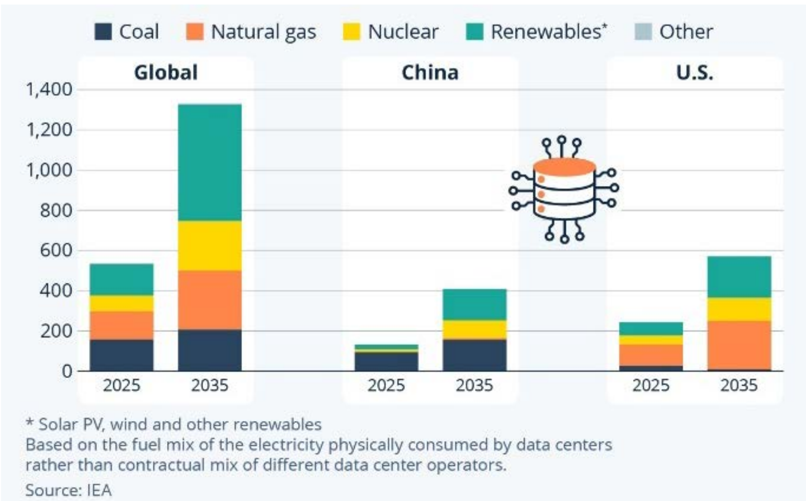


Figure 2. Electricity generation to supply data centres (in TWh)[6].

The rise of private fusion companies further reshapes the strategic landscape. Unlike previous generations of nuclear technology, fusion commercialization is being pursued through venture-backed firms operating across multiple jurisdictions. This introduces new questions regarding intellectual property, export controls, regulatory alignment, and state support. Governments are now confronted with strategic choices: whether to act primarily as funders of research, as market shapers through regulation and procurement, or as

[4] IEA, World Energy Outlook 2025.
[5] McKinsey Global Energy Perspective 2024; IEA, Energy and AI.
[6] https://www.statista.com/chart/34295/data-centers-electricity-generation-source/.

active partners in commercialization. These choices will influence not only domestic energy outcomes, but also international competitiveness and alliance structures.

In this context, fusion energy matters for geostrategy not because it will immediately transform the global energy mix, but because decisions taken in the 2020s will determine who controls the knowledge, infrastructure, standards, and industrial capacity underpinning fusion's future deployment. As with previous energy transitions, early strategic positioning is likely to yield long-term advantages. Understanding fusion through a geostrategic lens is therefore essential to navigate an increasingly complex, competitive, and decarbonising global energy system.

State of Fusion in 2025: From Research to Pre-Industrial Phase

By 2025, fusion energy has reached a stage where scientific research and engineering development increasingly overlap with early industrial strategy and commercialization planning. After decades of basic plasma physics research and critical investments in large international facilities, fusion is no longer viewed purely as a long-term scientific goal. Instead, it occupies an intermediate phase in which key technologies are being validated, multiple prototype concepts are under construction, and an emerging private sector is positioning for eventual deployment.

ITER and Public Fusion Programmes

At the forefront of the public effort remains the International Thermonuclear Experimental Reactor (ITER), the largest scientific infrastructure ever built to pursue controlled magnetic fusion. Located in Cadarache, France, ITER is designed to demonstrate the physical and technological feasibility of producing net energy from fusion reactions, aiming for a ten-fold energy gain ($Q \approx 10$) in deuterium-tritium operations in 2039[7].

The goal of ITER is to operate at 500 MW (for at least 400 seconds continuously) with 50 MW of plasma heating power input. No electricity will be generated at ITER, and it will be an experimental machine. The ITER Tokamak will be the largest ever built, with a plasma volume of 830 cubic metres, and a major radius of 6.2 m.

[7] https://www.iter.org/sites/default/files/media/2025-11/exe-ra-2024-ok-web.pdf.

Figure 3. Image: Drone view of the ITER tokamak and construction site. 14-05-2025
Photo: ITER Organization/EJF Riche.

ITER is funded and will be operated by seven member parties: China, the European Union (EU), India, Japan, Russia, South Korea and the United States. Switzerland participated through Euratom and F4E until 2021, though it is expected to rejoin in 2026 following subsequent negotiations with the EU. ITER also has technical cooperation agreements with Australia, Canada, Kazakhstan and Thailand[8].

The ITER project's design process began with a conceptual phase in 1988, following the idea's launch in 1985, with the final design approved in 2001, though detailed engineering continued, leading to the formal agreement to build it in 2007 and construction starting in 2013.

ITER has experienced multiple schedule delays and cost increases. Initial projections suggested that ITER construction would be completed in 2016, with the first experiments beginning in 2020, at a total cost of $10 billion (adjusted for inflation).

In 2016, the construction schedule was extended to 2025, with full operation expected by 2035, adding an additional $5.2 billion (adjusted for inflation) to the total cost. In July 2024, ITER announced that the facility would not be fully operational until 2039 and would with a final cost of $22 billion[9].

[8] https://www.iter.org/about/iter-members.
[9] https://www.congress.gov/crs-product/R48362.

ITER's continuing construction and component delivery—such as the installation of massive niobium-tin superconducting magnets—underscore both the technological scale and the persistent timeline challenges of fusion research. Despite periodic schedule adjustments and budget escalations, ITER's progress provides very useful information about components manufacturing, quality control, assembly phase issues, etc as well as the set up of an incipient fusion supply chain.

In parallel with ITER, regional programmes such as EUROfusion in Europe[10] coordinate research and design work toward a post-ITER device (often referred to as DEMO) that would exemplify a practical electricity-producing fusion plant. These programmes extend beyond pure plasma science into materials science, breeding blanket systems, tritium fuel cycles, and component testing, all essential to bridge the gap between experimental devices and industrial power plants.

Materials Validation and Infrastructure Development

A core technical bottleneck remains the behaviour of materials under intense neutron irradiation and high heat fluxes. Fusion energy systems produce neutron spectra and fluxes not routinely encountered in fission reactors or conventional power plants, making materials qualification an international priority.

One strategic initiative in 2025 is the IFMIF-DONES project in Spain[11], an accelerator-based high-flux neutron source designed to test candidate materials for future fusion reactors. Spain, the European Commission, and international partners have committed hundreds of millions of euros to its construction and operation, reflecting the broader focus on materials readiness as a prerequisite for having an operating fleet of fusion power plants.

Private Sector Momentum and Diversification

Historically, fusion research was dominated by public institutions and multilateral collaborations like ITER. However, by 2025, private fusion ventures have grown in

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[10] https://euro-fusion.org/.
[11] https://ifmif-dones.es/.

number, ambition, and funding. Fusion Industry Association 2025 report 12 indicates that over 50 private companies worldwide are active in developing diverse fusion concepts, from compact tokamaks and field-reversed configurations to alternative confinement systems and laser-driven approaches.

Figure 4. Distribution of fusion start-ups in 2025. Source: Fusion Industry Association 2025 report.[12]

Investment data from the Fusion Industry Association show a surge in funding to these private efforts, reaching record annual growth — a 178 % increase over the prior year — with total investments nearing $10 billion since 2021. While capital requirements remain high, this influx of private funds demonstrates both confidence in fusion's prospects and strategic interest from commercial and institutional investors alike. Venture capital, strategic corporate investors, and increasingly sovereign and institutional actors are shaping the sector. The report notes a shift from early speculative funding toward larger, milestone-based investment rounds tied to demonstrable technical progress.

12 https://www.fusionindustryassociation.org/fusion-industry-reports/.

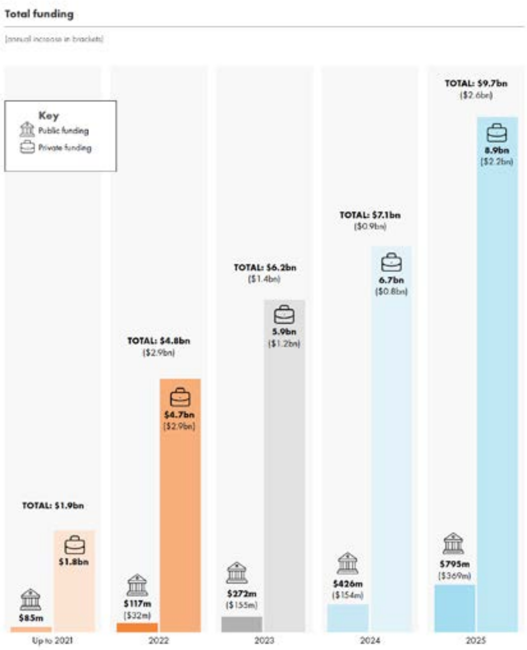

Figure 5.Total funds allocated to the development of fusion.

Source: Fusion Industry Association 2025 report.[12]

In the following table the top-5 best-capitalised fusion energy startups in 2025 are listed:

Company	Total Funding (approx.)	Headquarters	Fusion Concept / Technology	Major Prototype / Project	Top 3 Known Investors
Commonwealth Fusion Systems (CFS)	~$3.0 billion+	Devens, Massachusetts, USA	High-field Tokamak (HTS magnets)	SPARC & future ARC power plant	Breakthrough Energy Ventures; Eni; Google; Temasek
TAE Technologies	~$1.3 billion+	Foothill Ranch, California, USA	Field-Reversed Configuration (FRC)	Copernicus / Da Vinci (planned)	Google; Chevron; (Pre-merger) Rusnano (historic/legacy)
Helion Energy	~$1.03 billion	Everett, Washington, USA	Magneto-inertial / FRC fusion	Polaris prototype	Sam Altman; Reid Hoffman; Peter Thiel’s Mithril Capital Management

Pacific Fusion	~$900 million	Fremont, California, USA	Pulsed electromagnetic / inertial fusion tactic	Electromagnetic pulse fusion prototype (milestone-driven)	Not fully disclosed / milestone-based (lead investors not yet widely published)
SHINE Technologies	~$778 million	Janesville, Wisconsin, USA	Neutron testing & isotope support for fusion readiness	Test & isotope production facilities	Energy Ventures Group; Koch Disruptive Technologies; Nucleation Capital

Table 1. Summary of the top-5 best-capitalised fusion energy startups in 2025

One high-profile example is TAE Technologies, a company developing alternative fusion concepts that has partnered with the UK Atomic Energy Authority to commercialise auxiliary technologies such as neutral-beam systems, which have applications in medicine and industry on shorter timescales, and in December 2025 merged with Trump Media & Technology Group in all-stock transaction valued at more than $6 billion[13].

Technological maturity level and outstanding challenges

Fusion still faces the need of technological developments. Net electricity production and continuous operation have not yet been achieved. Materials testing, fuel cycle integration — particularly tritium breeding and handling — and cost-effective manufacturing at scale remain major challenges.

The next decade will be decisive in transforming fusion from an experimental quest into an industrial programme capable of delivering real energy solutions.

[13] https://tae.com/trump-media-and-technology-group-to-merge-with-tae-technologies/.

Artificial intelligence (AI) can significantly accelerate the development of fusion energy by addressing some of the most complex, data-intensive, and time-critical challenges in many critical aspects in the deployment of fusion power plants. From real-time plasma control using reinforcement learning and neural networks to actively manage plasma shape, position, and stability, to achieve RAMI (Reliability, Availability, Maintainability, Inspectability) targets in future fusion power plants by improving and optimizing fuel cycle, tritium management, and Operations.

Timelines to Grid Connection

Fusion energy development follows multiple parallel timelines, largely determined by the chosen confinement concept, development approach, and balance between physics risk and engineering complexity. Rather than a single “fusion date,” the field is characterized by a portfolio of pathways with different risk–reward profiles:

Public DEMO Programmes (ITER-based Tokamaks)

Public programmes anchored in ITER and followed by DEMO machines represent the most conservative and physics-validated pathway. These efforts prioritize full demonstration of plasma performance, tritium breeding, materials qualification, and regulatory acceptance before grid connection.

- Strengths: High confidence in physics, strong international governance, regulatory credibility
- Limitations: Long timelines, difficult to integrate innovations, complex international coordination, large machines, high capital intensity
- Indicative grid connection: ~2045–2050

Tokamak-based start-ups using high-field, high-temperature superconducting magnets (e.g. CFS, Tokamak Energy)

High-field tokamak startups leverage advances in high-temperature superconductors (HTS) to significantly reduce machine size and accelerate iteration cycles. These companies aim to bridge public science and private delivery by de-risking key physics while compressing engineering timelines.

- Strengths: Strong physics basis, faster iteration than ITER-class machines, smaller machines, agile approach
- Limitations: Materials lifetime, tritium systems, integration
- Indicative grid connection: ~2035

Field-Reversed Configuration (FRC) Approaches (e.g. Helion, TAE)

FRC-based concepts pursue compact, pulsed, and often semi-aneutronic designs, sometimes bypassing steam cycles through direct energy conversion. These approaches prioritize speed and simplicity, accepting higher physics risk.

- Strengths: Potentially faster path, smaller machines, lower capital cost
- Limitations: Plasma stability, repetition rate, and net electricity still unproven
- Indicative grid connection: ~2031–2033

Stellarator-based Start ups (e.g. Proxima Fusion)

Advanced stellarator concepts aim to exploit inherently stable plasma configurations combined with modern computational design and advanced manufacturing. While physics is well established, engineering complexity remains high.

- Strengths: Intrinsic plasma stability, steady-state operation
- Limitations: Manufacturing complexity, limited operational experience at scale, less mature concepts than tokamaks
- Indicative grid connection: ~2037

Inertial Fusion Energy (IFE) (e.g. Xcimer Energy)

IFE builds on ignition breakthroughs but faces challenges in repetition rate, target fabrication, and energy efficiency. While scientifically promising, engineering gaps remain before power plant operation.

- Strengths: High power density potential, separation of driver and chamber
- Limitations: Industrial scalability, cost, and system integration
- Indicative grid connection: ~2040

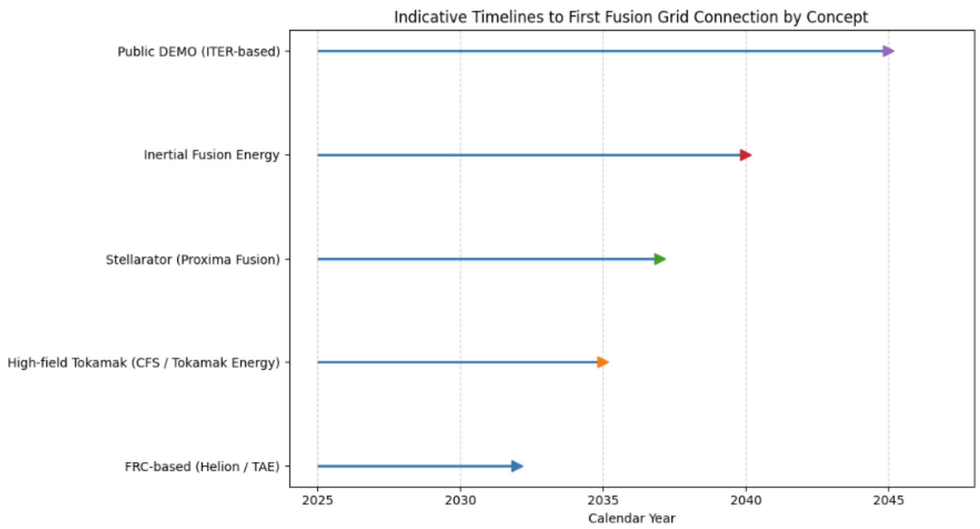

Figure 6. Indicative timelines to first grid connection for major fusion energy development pathways. Dates reflect expert consensus estimates based on current technology readiness, announced roadmaps, and system integration challenges. Arrows indicate first-of-a-kind grid-connected demonstrators, not full commercial deployment.

A key element for Fusion Energy Deployment: Regulation

As fusion energy moves toward prototype demonstration and early commercial deployment, regulation becomes one of the most critical non-technical determinants of success. The regulatory framework governing fusion will shape not only safety outcomes, but also investment decisions, siting of facilities, pace of deployment, and long-term industrial competitiveness.

Fusion developers are now designing facilities intended to connect to the grid, supply electricity markets, and operate under commercial conditions. These systems must be licensed, insured, financed, and accepted by the public. In this context, regulation must strike a careful balance: it must ensure protection of workers, the public, and the environment, while remaining proportionate to the actual risk profile of fusion technologies.

History shows that regulatory misalignment can significantly delay energy transitions. Overly conservative frameworks increase costs, lengthen timelines, and discourage private capital. Conversely, clear, predictable, and risk-informed regulation can accelerate learning-by-doing, foster innovation, and anchor new industrial ecosystems. For fusion energy—where multiple technology pathways are advancing in parallel—regulatory clarity is now a strategic necessity rather than a future concern.

Fundamental Differences Between Fusion and Fission

The case for a distinct regulatory approach for fusion is grounded in fundamental physical and operational differences between fusion and nuclear fission systems.

Fission reactors rely on controlled chain reactions, which require complex engineered systems to manage reactivity, decay heat, and accident scenarios. Fusion reactions, by contrast, are inherently self-limiting. The fusion process ceases immediately if precise plasma conditions are not maintained, eliminating the possibility of runaway reactions. There is no possibility of chain reaction.

Fission plants contain large inventories of fissile material that must be safeguarded over decades. Fusion systems operate with very small quantities of fuel, primarily deuterium and tritium. Tritium presents radiological and environmental hazards, but it does not pose the same proliferation or long-term security risks as fissile materials. For example, Tritium half-life is 12.32 years.

Fission produces high-level radioactive waste requiring isolation for millennia. Fusion produces no fission products; its waste consists mainly of neutron-activated materials, many of which decay to low-level waste within decades. This distinction has major implications for waste classification, disposal pathways, and long-term liabilities.

Credible accident scenarios for fusion are dominated by localized releases of tritium or activated dust, rather than large-scale off-site radiological releases. As a result, emergency planning requirements for fusion facilities are fundamentally different from those for fission reactors.

Why Fusion Regulation Must Be Specific

Given fusion's distinct risk profile, regulation should focus on hazard-based oversight rather than reactor-centric licensing. Key regulatory domains include:

- Management of radioactive materials (especially tritium)
- Occupational radiation protection
- Environmental releases
- Conventional industrial safety

This approach aligns fusion regulation more closely with particle accelerators and research facilities than with nuclear power reactors.

Fusion technologies will mature through a sequence of increasingly integrated prototypes. Regulation must therefore be adaptive, allowing lessons learned from early facilities to inform subsequent requirements. Overly prescriptive rules at early stages risk freezing designs prematurely and increasing costs without commensurate safety benefits.

Private investment now plays a central role in fusion development. Regulatory uncertainty directly translates into higher financing costs. Clear licensing pathways, defined timelines, and regulatory stability are essential to mobilize the scale of capital required for fusion deployment.

Impact of regulatory frameworks on the deployment of fusion technologies

Regulatory frameworks increasingly function as tools of industrial policy.

Proportionate regulation enables faster licensing, earlier grid connection, and rapid learning.

Overly conservative regulation delays projects, increases costs, and drives developers to more favorable jurisdictions.

Early regulatory leadership allows countries to shape international norms and standards, reinforcing long-term competitiveness.

Countries that move first to establish fusion-appropriate regulation are more likely to attract prototype facilities, supply chain investment, and skilled talent—key ingredients of a future fusion industry. This is somehow reflected in the emerging fusion industry distribution, being US the leader.

Status of Fusion Regulation in Key Jurisdictions

United States

The United States has taken the most explicit steps to define fusion-specific regulation. Fusion facilities are regulated under a byproduct materials framework rather than as fission reactors.

Key milestones include:

- 2009: NRC affirms jurisdiction over fusion
- 2019–2022: Congressional direction via NEIMA
- 2023: NRC decision to regulate fusion under 10 CFR Part 30
- 2024: ADVANCE Act codifies fusion as particle accelerators under federal law

This framework enables faster licensing while maintaining safety and environmental protections.

United Kingdom

The United Kingdom has taken one of the most proactive and explicit approaches in the world to develop a regulatory regime that is proportionate to the actual risk profile of fusion energy, avoids unnecessary hurdles, and provides clarity and confidence for both public and private developers. This regulatory strategy is now embedded in statute, supported by formal consultations, and linked directly to national planning policy — a combination that gives the UK a strong first-mover advantage. This approach supports national initiatives such as STEP and positions the UK as a global fusion hub.

One of the UK's defining regulatory innovations is the explicit exclusion of fusion facilities from the traditional nuclear licensing regime under the Nuclear Installations Act 1965.

The UK government has legislated to ensure that fusion facilities are not automatically regulated as “nuclear installations”, reflecting their very different hazard profile compared to fission reactors. This legal change provides important clarity and proportionality for fusion developers.

Fusion energy facilities do not require a nuclear site licence under the Nuclear Installations Act. They are therefore not regulated by the Office for Nuclear Regulation (ONR) in the same way as fission reactors. Instead, fusion facilities will continue to be regulated primarily by the Environment Agency (EA) and the Health and Safety Executive (HSE).

European Union

In policy and regulatory development, the EU is actively working toward a dedicated fusion strategy that could lead to a more structured regulatory environment in 2026, reflecting growing recognition of fusion’s potential role in the future energy mix. Stakeholders, including policymakers and industry groups, have called for clearer, harmonised regulatory principles that distinguish fusion from nuclear fission) regulation to provide certainty for investors and developers. The European Parliament and the Commission are engaging in consultations and planning to embed fusion within broader industrial and net-zero frameworks (for example, discussions about its categorisation under the Net Zero Industry Act), but detailed licensing rules for commercial fusion facilities remain in early stages of development or under discussion rather than fully codified across the EU.

In summary, fusion regulation in the EU is evolving from foundational research governance toward emerging policy initiatives aimed at enabling future commercialisation, but a comprehensive, specific regulatory regime for fusion power plants does not yet exist — it is anticipated as part of upcoming EU strategy and legislative planning.

Nordic states (Finland, Sweden, Denmark and Norway)

Finland stands at the forefront of fusion regulation readiness in the Nordic countries, driven by its planned overhaul of nuclear law and clear statutory treatment of fusion under radiation regulation.

Finland is taking a proactive stance toward fusion regulation and broader nuclear law reform.

In June 2025, the Finnish Government sent a draft revision of the Nuclear Energy Act out for public comment. The proposal represents a major overhaul of a law that had been in force for more than 35 years and has been amended repeatedly. The reforms aim to modernise the framework, make it more innovation-friendly, and bring it into alignment with current technological and legislative realities. Fusion research and experimental use of fusion reactors would not fall under the Nuclear Energy Act governing fission facilities. Instead, such activities are clearly stated to be regulated under the Radiation Act. This distinction reflects the regulatory reality that fusion's hazard profile and operational needs differ from conventional nuclear reactors.

The Radiation and Nuclear Safety Authority (STUK) will serve as the licensing authority for activities regulated under radiation law, while facilities involving fission reactions will continue to be regulated under nuclear facility law. The draft restructuring separates decisions on radioactive waste and safeguards from technical safety matters, allowing for modular licensing and clearer governance. The revised Act is scheduled to enter into force on 1 January 2027 if approved.

Sweden was identified as next in readiness. Its existing nuclear legislation already explicitly includes fusion reactors, but those laws are heavily oriented around fission-based regulatory requirements. This means that Sweden's rules can be applied to fusion, but developers may need to navigate comprehensive fission-focused conditions that are not optimised for fusion's distinctive hazard and risk profile.

Both Denmark and Norway were noted to have older nuclear regulatory frameworks that do not specifically mention fusion energy. This creates political and procedural uncertainty for fusion projects, as the absence of explicit fusion references can delay clarity in licensing pathways. Neither country has yet adopted fusion-specific statutory language or strategies to make their legal environment particularly attractive for fusion development[14].

[14] Framework of siting criteria and initial assessment for siting the Novatron 3 facility in Nordic region, https://static1.squarespace.com/static/634d70f7acf00f3d7942848e/t/68f5cc3af2297812c492e052/1760939066885/VTT+report.pdf.

Japan

Japan's nuclear legal architecture was built around fission: reactor licensing, nuclear fuel material controls, and site regulation. The most important consequence for fusion is definitional: fusion devices are not "reactors" under the legal meaning used for fission regulation, so the main fission-focused statute (the Reactor Regulation Act / reactor framework under the Atomic Energy Basic Act structure) does not automatically map onto fusion facilities. The practical result is that Japanese fusion machines have been handled under the radioisotope / radiation-generating device paradigm rather than the fission "reactor" paradigm.

Japan's fusion devices (especially research-scale machines) have typically fit into regulation governing radioisotopes and radiation-generating equipment, for example JT-60SA, the largest operating tokamak in the world, which has been regulated as a plasma generation device under the radioisotope/radiation framework.

Under existing law, fusion devices can be regulated as radiation generation devices, but the present framework has limitations for commercial-direction fuel cycles—especially tritium. Using tritium as fuel would require changes/updates so that tritium-fuelled plasma generators can be accommodated appropriately.

Japan's nuclear regulator (NRA) has been increasingly explicit that it is tracking emerging technology trends, including R&D in fusion, as part of its forward-looking work on radiation hazard prevention regulation.

China

China's biggest recent regulatory milestone is a Ministry of Ecology and Environment (MEE) notice titled "Notice on Matters Concerning the Radiation Safety Management of Fusion Devices", dated April 2025. China's institutional structure places nuclear and radiation safety regulation under the Ministry of Ecology and Environment (MEE), including the national nuclear safety administration functions. The 2025 fusion notice explicitly assigns MEE responsibility for radiation safety permitting and indicates regional supervision stations conduct day-to-day oversight/inspection.

The 2025 notice does is effectively declare fusion devices in-scope of the radiation safety regulatory system and provide a fusion-specific classification and administrative pathway for permits/EIA coordination.

China's fusion framework is explicitly moving toward graded/classified regulation (a familiar approach in China's radiation device management). The 2025 notice and associated presentations describe fusion devices being grouped along lines such as: plasma physics experimental devices, deuterium–tritium fusion experimental devices, and fusion energy application devices being then managed according to corresponding risk and regulatory handling.

This is significant because DT experiments and "application devices" are precisely where tritium inventories, activated materials, and industrial interfaces become dominant safety drivers—so a one-size-fits-all rule set would either overburden low-hazard experiments or under-specify higher-hazard systems.

China's official messaging around the 2025 notice emphasizes that fusion does not map neatly to traditional fission reactor supervision, and that the regulator is pursuing science-based regulation and development of a fusion regulatory standards system.

Dimension	Nuclear Fission	Fusion
Reaction behaviour	Self-sustaining chain reaction	Self-limiting
Fuel inventory	Large fissile inventories	Small quantities (D–T)
Proliferation risk	High	Very low
Waste type	High-level, long-lived	Activated materials, shorter-lived
Accident potential	Large off-site consequences	Localized, limited
Emergency planning	Extensive	Limited, site-specific
Appropriate regulation	Reactor-based licensing	Hazard-based oversight

Table 2. Fusion vs Fission: Regulatory-relevant differences

Country / Region	Regulatory Approach	Status
United States	Byproduct material / accelerator	Defined, codified
United Kingdom	Proportionate, fusion-specific	Defined, evolving
European Union	National-level approaches	Fragmented
Finland	Proportionate, fusion-specific	In progress
Japan	Adapted nuclear framework	Gradual adaptation
China	Integrated national oversight	Centralized, state-led

Table 3. Status of Fusion Regulation by Country (2025)

Enabling technologies for fusion: the key role of artificial intelligence, high performance computing and quantum computing

The physics and engineering of fusion present extraordinary complexity: plasmas at hundreds of millions of degrees must be generated, confined, and sustained; materials must endure intense heat and neutron loads; reactors must operate reliably as industrial power plants. Every facet of this challenge involves multiscale, nonlinear, high-dimensional physics that are far beyond the reach of human intuition or traditional experimentation alone.

Fusion devices involve tightly coupled, nonlinear phenomena spanning orders of magnitude in space and time: turbulent plasmas, superconducting magnets, neutron-irradiated materials, tritium fuel cycles, power conversion systems, and real-time control.

Historically, progress in fusion was constrained by experimental iteration speed. Design choices were validated by building machines, operating them for years, learning from failure, and then constructing the next generation. This approach is not compatible with the timescales required for industrial deployment.

This is why the integration of artificial intelligence (AI), high-performance computing (HPC), and emerging quantum computing into the core of fusion development workflows is a game changer. These technologies allow fusion to move from a hardware-limited paradigm to a computation-accelerated engineering discipline, compressing decades of learning into years.

High-Performance Computing and Integrated Simulation Frameworks

Predictive simulation of fusion plasmas requires solving nonlinear kinetic and magnetohydrodynamic equations across immense scale separations[15, 16, 17]. Traditional experimental iteration cannot match the breadth of parameter space that HPC models can traverse. Exascale computing capability is now recognized as a requirement for capturing turbulent transport, edge–core coupling, and electromagnetic effects with fidelity nearing experimental conditions[17].

A recent collaboration between Commonwealth Fusion Systems, NVIDIA, and Siemens demonstrates how modern AI-enabled simulation libraries and digital engineering tools can compress fusion design cycles further.

According to CFS, the combination of NVIDIA's AI and simulation SDKs (such as cuQuantum, cuFFT, cuBLAS, and TensorRT) with Siemens' Xcelerator digital twin tools enables GPU-accelerated plasma physics solvers that leverage thousands of GPU cores to shave months off simulation time; AI-assisted surrogate models that replace expensive numerical kernels with learned approximations without significant loss of fidelity; and End-to-end digital engineering workflows that connect plasma simulations with finite-element structural and electromagnetic analyses directly in Siemens' environment.

By harnessing GPU-accelerated simulation stacks, CFS reports orders-of-magnitude speedups compared to CPU-only workflows, enabling more design iterations within the same calendar time and improving the fidelity of *end-to-end plant performance predictions* (including magnets, structural loads, and integrated plasma behaviour)[18].

Artificial Intelligence: from control to design optimization

AI is now embedded across the fusion innovation stack, not just in isolated research projects.

[15] Jenko, F. et al., Electron temperature gradient driven turbulence. *Physics of Plasmas*, Vol. 7, pp. 1904–1910 (2000).
[16] Chang, C. S. et al., Whole-device modelling of plasma transport in fusion plasmas. Physics of Plasmas, Vol. 24, 055503 (2017).
[17] Birdsell, J. et al., Exascale computing and fusion energy sciences. Journal of Physics: Conference Series, Vol. 1258, 012006 (2019).
[18] How NVIDIA AI and simulation libraries and Siemens tools can accelerate fusion energy | The Tokamak Times.

AI for plasma control

Deep reinforcement learning and other machine-learning methods have been shown in academic research to outperform classical controllers in maintaining plasma shape and suppressing instabilities[19, 20]. These methods are viable for plant-scale systems only if embedded within computational frameworks that can train on simulated data and then generalize to new operational conditions.

AI is being used to

Predict disruption precursor signatures, avoiding costly plasma terminations; optimize real-time magnet coil control strategies using models trained on simulated and experimental data; and inform control system architecture for future devices where human-tuned feedback loops are impractical.

These capabilities are essential because disruption avoidance and active stability control directly influence machine availability — a critical economic parameter for fusion power plants[19, 21].

AI-accelerated design and surrogate models

AI also drives rapid prototyping of designs. Neural networks serve as surrogate physics models, capturing complex dependencies (e.g., turbulence transport coefficients, stability margins) at a fraction of the compute cost of full solvers[22, 23].

This approach has been integrated with Siemens' digital twin environment, enabling: fast evaluation of candidate designs within a coherent digital engineering workflow, Multi-objective optimization across performance, cost, and manufacturability, as well as exploration of unconventional design concepts that would be impractical to test physically.

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[19] Degrave, J. et al., Magnetic control of tokamak plasmas through deep reinforcement learning. *Nature*, Vol. 602, pp. 414–419 (2022).
[20] Kates-Harbeck, J. et al., Predicting disruptive instabilities in controlled fusion plasmas through deep learning. *Nature*, Vol. 568, pp. 526–531 (2019).
[21] van Milligen, B. P. et al., Machine learning control for tokamak plasmas. *Nuclear Fusion*, Vol. 62, 056019 (2022).
[22] Bishop, C. M., *Pattern Recognition and Machine Learning*. Springer, 2006.
[23] Sanchez, R. et al., Gyrokinetic turbulence simulations with reduced models. *Nuclear Fusion*, Vol. 59, 056014 (2019).

Such surrogate models — trained on HPC-generated datasets and cached for real-time evaluation — enable iterative design loops that compress what once took months into days or hours.

Type One Energy builds directly on decades of stellarator optimization research, where acceptable confinement and stability are achievable only through large-scale numerical optimization of three-dimensional magnetic configurations[24,25,26]. Without modern HPC, commercial stellarator development would be infeasible. Similarly, Thea Energy relies on computational optimization to explore magnetic configurations and operational regimes that would require prohibitively long experimental campaigns.

Other good example is Proxima Fusion that is involved in the project "AI for Fusion Engineering", backed by Germany's Federal Ministry of Education and Research, with partners at Forschungszentrum Jülich, the Technical University of Munich, and the University of Bonn. The focus of this project is on using geometric machine learning and deep learning to address the complex geometry problems inherent in stellarator design — learning to predict and optimize plasma behavior and field quality much faster than existing numerical methods alone can.

AI applied to materials and components for fusion

Fusion materials must simultaneously withstand: high neutron fluence, extreme thermal loads, and chemical and mechanical stresses.

AI is used to accelerate materials discovery and lifetime prediction by learning complex nonlinear responses to irradiation and thermal gradients. Studies have shown that AI-assisted materials screening can reduce experimental search spaces by orders of magnitude compared to trial-and-error methods[27].

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[24] Hirshman, S. P., Whitson, J. C., Steepest-descent moment method for three-dimensional equilibrium calculations. *Physics of Fluids*, Vol. 26, pp. 3553–3568 (1983).
[25] Landreman, M., Paul, E. J., Magnetic fields with precise quasisymmetry for plasma confinement. *Physical Review Letters*, Vol. 128, 035001 (2022).
[26] Helander, P. et al., Stellarator and tokamak plasmas: a comparison. *Plasma Physics and Controlled Fusion*, Vol. 54, 124009 (2012).
[27] Butler, K. T. et al., Machine learning for molecular and materials science. *Nature*, Vol. 559, pp. 547–555 (2018).

Digital twins: continuous learning through data and simulation

Digital twins represent a synthesis of HPC, AI, and industrial simulation tools. In fusion, digital twins ingest real-time diagnostics, match them to physics models, and predict future states of the system.

Scientific work on digital twins in fusion demonstrates that such systems can forecast disruptions before they occur, evaluate multiple control trajectories in real time, and provide operators with actionable insight into machine health and performance[28,29].

For example, the Siemens-accelerated digital engineering environment used by CFS extends these ideas into an industrial context, where digital twins are core operational tools for pilot plants and future commercial reactors. By linking plasma simulators, structural analysis, and control models into a single virtual prototype, the workflow ensures that design decisions account for the full physics and engineering context, reducing lower-order surprises during construction and commissioning[18].

Quantum computing as an emerging enabling technology

Even as AI and HPC drive the near-term fusion agenda, quantum computing is positioned as a long-horizon technology for problems that scale combinatorially or involve complex quantum chemistry.

Examples of domains where quantum methods could eventually surpass classical approaches include: strongly correlated materials modeling, Plasma–surface interaction calculations with full quantum fidelity, and optimization problems with exponentially large search spaces[30,31].

In practice, quantum computing is expected to be integrated via hybrid quantum–classical workflows, where quantum subroutines accelerate specific kernels within a larger HPC + AI pipeline. While practical quantum advantage in fusion remains an open research

[28] Pankin, A. et al., Toward digital twins for fusion reactors. *Fusion Engineering and Design*, Vol. 146, 140–146 (2019).
[29] Rea, C. et al., Disruption prediction and avoidance in tokamaks using real-time data. *Fusion Science and Technology*, Vol. 74, pp. 1–13 (2018).
[30] Preskill, J., Quantum computing in the NISQ era and beyond. *Quantum*, Vol. 2, 79 (2018).
[31] McArdle, S. et al., Quantum computational chemistry. *Reviews of Modern Physics*, Vol. 92, 015003 (2020).

frontier, early engagement ensures that fusion R&D is ready to exploit it as hardware matures.

Computational technologies as catalysts for the development of fusion

The integrated impact of AI, HPC, and simulation ecosystems tools allows:

- Design acceleration — Digital exploration replaces slow experimental sequences, enabling rapid convergence on viable power plant configurations.
- Risk mitigation — Predictive models highlight failure modes early in design, reducing costly rework.
- Operational reliability — AI-based control and digital twins improve uptime, extending component life and controlling degradation.
- Capital efficiency — Fewer physical prototypes and targeted experiments reduce cash and time expenditures.

Global Power Dynamics in Fusion Development

Fusion has moved decisively from a long-horizon scientific ambition into the domain of strategic technology competition. While no commercial fusion power plants are yet operating, the scale, structure, and direction of investment reveal that major powers increasingly treat fusion as a determinant of future economic strength, energy security, and technological sovereignty. Fusion is now discussed alongside semiconductors, artificial intelligence, and advanced manufacturing as a platform technology with far-reaching spillover effects.

Unlike previous energy transitions, fusion development is unfolding during a period of systemic geopolitical rivalry. Governments are no longer funding fusion solely as a public-good scientific endeavor; they are embedding it within national industrial strategies, security doctrines, and long-term competitiveness agendas. As a result, the fusion landscape reflects divergent political economies: market-driven experimentation in the United States, state-coordinated planning in China, science-led but fragmented governance in Europe, and supply-chain positioning by advanced manufacturing economies such as Japan and South Korea.

This sub chapter describes fusion through the lens of power and value capture, focusing not on who achieves fusion first, but on who controls the industrial ecosystems, intellectual property, supply chains, and standards that will determine long-term geopolitical advantage if fusion reaches commercial maturity.

United States: Fusion as Industrial and Strategic Leverage

The United States has adopted a fusion development model intends to combine federal risk absorption with private-sector execution. Public funding, primarily through the U.S. Department of Energy (DOE), supports foundational plasma science, materials research, and enabling technologies, while private companies drive system design, construction, and commercialization.

Federal signalling accelerated markedly after 2022. The Department of Energy's (DOE) Fusion Energy Sciences (FES) program, historically focused on plasma science, was repositioned through the DOE Fusion Science and Technology Roadmap to emphasize pilot plants, grid relevance, and supply-chain readiness. Annual federal fusion spending now stands at approximately USD 800–900 million across DOE offices, including FES, Advanced Research Projects Agency–Energy (ARPA-E), and inertial fusion programs at the National Nuclear Security Administration. When ancillary infrastructure, high-performance computing, and materials programs are included, effective public investment exceeds USD 1.2 billion per year.

Crucially, this public base has catalyzed unprecedented private capital. Since 2018, U.S.-based fusion startups—such as Commonwealth Fusion Systems, Helion Energy, TAE Technologies, and Zap Energy—have collectively raised an estimated USD 6–7 billion in private funding. These investments are not merely speculative; they are structured around hardware milestones, power purchase agreements, and defense-adjacent applications in some cases. The Genesis mission announced in 2023[32] ,which framed fusion as a near-term strategic priority, served as a deliberate signal to markets and allies that fusion sits alongside AI, semiconductors, and advanced manufacturing in the U.S. strategic competition framework. It has to be mentioned that the need of energy sources to power AI, quantum computing, and autonomous systems is mentioned explicitly in the US

[32] https://www.whitehouse.gov/presidential-actions/2025/11/launching-the-genesis-mission/.

National Security Strategy document released in November 2025 “The United States must at the same time invest in research to preserve and advance our advantage in cutting-edge military and dual-use technology, with emphasis on the domains where U.S. advantages are strongest. These include undersea, space, and nuclear, as well as others that will decide the future of military power, such as AI, quantum computing, and autonomous systems, plus the energy necessary to fuel these domains”[33].

Fusion is increasingly embedded in U.S. narratives of strategic competition, particularly with China. Congressional reports and executive strategies link fusion to broader priorities in AI, advanced manufacturing, energy independence, and national security. Fusion is treated as a platform capability whose enabling technologies — high-field magnets, power electronics, control software, advanced materials — reinforce U.S. leadership across multiple sectors. The implicit logic mirrors that of AI: dominance accrues to those who industrialize first, not necessarily those who discover first.

The U.S. advantage lies in its ability to translate laboratory success into scalable firms. National laboratories provide validation, while private companies assume engineering risk. This model privileges speed and optionality over centralized certainty. However, it also embeds vulnerability: fragmented efforts could duplicate infrastructure, and private timelines may clash with grid realities. Still, as of 2025, the U.S. remains the only jurisdiction where fusion is treated explicitly as both a future energy backbone and a pillar of strategic power projection.

Commercialization pathways in the United States are deliberately pluralistic. Magnetic confinement, inertial fusion, magneto-inertial hybrids, and alternative concepts are all funded to varying degrees, reflecting a strategic preference for portfolio competition. This contrasts sharply with the single-architecture bets of earlier decades. The DOE’s milestone-based public–private partnership programs, funded at roughly USD 50–75 million per award over several years, are designed less to “pick winners” than to de-risk multiple pathways until grid-relevant performance metrics emerge.

From an industrial-policy perspective, fusion is increasingly aligned with re-shoring agendas. Advanced manufacturing techniques—additive manufacturing of vacuum vessels, domestic production of REBCO superconducting tape, and neutron-tolerant

[33] https://www.whitehouse.gov/wp-content/uploads/2025/12/2025-National-Security-Strategy.pdf.

alloys—are framed as dual-use capabilities with spillovers into aerospace and defense. Several fusion firms maintain active relationships with the Department of Defense, particularly around pulsed power, compact reactors, and space propulsion. While these programs are modest in budgetary terms, they reinforce the perception of fusion as a strategic technology rather than a purely civilian one.

Strategic signaling also extends internationally. U.S. officials increasingly reference fusion in bilateral technology dialogues with allies, positioning American firms as preferred partners for future demonstration plants. This has the effect of locking in standards and intellectual property norms early. The United States' relatively permissive regulatory stance—fusion is regulated separately from fission, with lighter licensing burdens—further enhances its attractiveness as a development hub, accelerating talent inflows from Europe and Asia.

Despite these constraints, the U.S. model reflects a strategic calculation: fusion leadership will be secured by those who integrate science, capital markets, and industrial execution faster than rivals. In this framing, early commercial demonstration—even at high cost—confers geopolitical advantage by anchoring supply chains and shaping global expectations. The United States is therefore less concerned with achieving perfect economic fusion in the first instance than with ensuring that, when fusion becomes viable, its firms, standards, and alliances define the field.

China: Fusion as Technological Sovereignty

China's fusion strategy is best understood through the lens of state-driven technological sovereignty. Fusion is embedded within a broader doctrine that prioritizes long-term control over foundational technologies, even when near-term economic returns are uncertain. Unlike market-led models, China's approach emphasizes continuity, infrastructure accumulation, and alignment with national planning cycles.

China's fusion program is embedded in long-term national science and technology planning. Public funding for fusion is estimated at $1.2–1.7 billion per year, exceeding recent U.S. federal allocations and characterized by high stability and continuity. This funding supports flagship projects such as EAST (Experimental Advanced Superconducting Tokamak) and CFETR, which is positioned as a bridge between experimental devices and a future power plant. Unlike ITER, these facilities are nationally controlled, enabling faster iteration and tighter integration with domestic industry.

Fusion development is led by state institutions rather than venture-backed startups, reflecting China's preference for centralized coordination over entrepreneurial diversity.

Fusion is explicitly framed as part of China's technological self-reliance agenda. Mastery of superconductors, tritium breeding, and high-heat-flux materials is treated as strategically equivalent to semiconductors or aerospace engines. This framing justifies sustained investment despite long timelines, insulating fusion programs from short-term political cycles.

The civil–military dimension is also significant. While China publicly emphasizes peaceful energy applications, fusion-relevant research overlaps with military interests in pulsed power, directed energy, and compact power sources. The doctrine of military–civil fusion ensures that advances in one domain are rapidly transferred to the other, amplifying strategic returns on investment.

Internationally, China leverages fusion participation to shape norms while retaining strategic autonomy. Its engagement in ITER provides access to global scientific networks, yet parallel national programs ensure that critical knowledge does not remain externally dependent. Talent development is systematic, with fusion expertise cultivated across universities, state laboratories, and industrial research centres.

United Kingdom: Fusion as a National Industrial Bet

The United Kingdom stands out as Europe's most strategically assertive fusion actor. Fusion is framed not merely as science but as a national industrial mission, aligned with energy security, regional development, and post-Brexit technological identity.

Governance is centred on the UK Atomic Energy Authority (UKAEA), which functions not only as a research body but as a project developer and industrial anchor.

The UK's flagship initiative, the STEP (Spherical Tokamak for Energy Production) programme, aims to deliver a grid-connected fusion prototype in the early 2040s. Unlike ITER or DEMO, STEP is explicitly designed as: a power-producing facility, a first-of-a-kind industrial demonstrator, a catalyst for domestic supply-chain development.

West Burton, located south of the city of Sheffield, has been selected as the site for STEP, lending credibility to the project while also serving as a catalyst for a nationwide public engagement campaign across the United Kingdom to raise awareness and understanding of fusion energy[34].

The UK has committed £410 million in new funding in 2025, bringing total fusion commitments into the multi-billion-pound range[35]. While smaller than ITER-scale spending, UK funding is directed at commercialization outcomes.

Equally important is regulatory positioning. The UK has established a bespoke fusion regulatory framework, deliberately avoiding classification of fusion facilities as nuclear fission reactors. This regulatory clarity is a strategic asset, enabling faster deployment and attracting private companies. Part of this strategy has focused on creating a hub for fusion companies in the Culham Campus where UAKEA is located, 'The Fusion Cluster', including a programme on workforce creation for fusion technologies.

UK also signed with US a major strategic partnership to accelerate fusion development, focusing on R&D, knowledge sharing, and skills in November 2023[36] This agreement has been reinforced under the Technology Prosperity Deal (TPD) signed in September 2025 focusing on combining expertise, resources, and AI to speed up commercial fusion, using shared research, test facilities, and aligning regulations for abundant, clean energy. These partnerships aim to integrate AI for advanced simulations, coordinate experiments, and foster private sector investment to accelerate the development of fusion power plants, creating jobs and boosting energy security[37].

Europe: Scientific Leadership Without Industrial Sovereignty

Europe occupies a paradoxical position in global fusion dynamics. It retains unmatched scientific credibility through ITER and a dense network of national laboratories, yet struggles to convert this leadership into industrial leverage. The European fusion

[34] https://stepfusion.com/west-burton/
[35] https://www.gov.uk/government/news/25-billion-for-world-first-prototype-fusion-energy-plant.
[36] https://www.gov.uk/government/news/uk-and-us-form-major-partnership-to-accelerate-global-fusion-energy-development.
[37] https://www.whitehouse.gov/presidential-actions/2025/09/memorandum-of-understanding-between-the-government-of-the-united-states-of-america-and-the-government-of-the-united-kingdom-of-great-britain-and-northern-ireland-regarding-the-technology-prosperity-de/.

ecosystem has been shaped by decades of multilateral governance, risk aversion, and public-sector dominance—an architecture optimized for scientific consensus rather than strategic speed.

ITER remains the centerpiece. With a total projected cost exceeding EUR 20 billion over its lifetime, ITER has anchored Europe's role as the world's primary convenor of fusion science. Complementing ITER is the European roadmap toward DEMO, a demonstration power plant envisioned for the 2040s. The EU's annual fusion-related spending, including Euratom programs and national co-funding, is approximately EUR 1–1.2 billion, making Europe's public investment comparable in scale to that of the United States.

ITER represents a triumph of international collaboration and engineering capability. However, it also illustrates Europe's structural challenge: large-scale scientific leadership does not automatically translate into industrial dominance. ITER is not designed as a power plant, nor as a commercialization vehicle.

Yet this investment profile reveals a structural imbalance. Funding is heavily weighted toward large facilities and long timelines, with limited mechanisms for rapid industrial spin-out. European private fusion startups exist—particularly in Germany —but they operate at a fraction of the capital intensity seen in the U.S.

Europe's fusion ecosystem is fragmented across EU institutions, national laboratories, and a relatively small private sector. Annual public fusion spending across the EU is estimated at €0.8–1.0 billion, dominated by ITER-related commitments. Private fusion investment remains modest at €1–1.5 billion cumulatively, a fraction of U.S. levels.

Company	Approx. funds raised / capitalization	Fusion concept (brief)	Country	Main investors / supporters
Marvel Fusion	**€400M**	Laser-driven inertial confinement (short-pulse lasers / target implosion)	Germany (Munich).	EQT Ventures, Siemens Energy Ventures, EIC Fund, Tengelmann, Bayern Kapital and others.
Proxima Fusion	**≈€200M**	Quasi-isodynamic **stellarator** (magnetic confinement variant focused on steady operation).	Germany (Munich origin; links to Max-Planck IPP).	Cherry Ventures, Balderton Capital; UVC Partners, DTCF, redalpine, others.

Focused Energy	**≈ €175M**	Laser-based inertial fusion (engineering prototype and integrated design).	Germany / US (dual US-German operation; active in Germany).	Strategic tie-ups with RWE, state of Hesse; private investors tied to US and EU funds.
Renaissance Fusion	**≈ €61.5M**	Compact stellarator / magnetic confinement with HTS magnets and liquid-metal walls (materials focus).	France	Led by funds including Crédit Mutuel Impact and participation by climate/VC investors.)
Gauss Fusion	**€10m grant from Germany's Federal Ministry of Education and Research (BMBF)**	Tokamak / megaproject ambitions (plans for large “GIGA” commercial plant).	Germany.	Public (BMBF) and venture supporters; industrial partnerships being developed.
Novatron Fusion	**≈ €18M**	Mirror / alternative magnetic confinement (Swedish research spin-out).	Sweden.	Axon Partners Group, together with St1 and a consortium of investors, Santander InnoEnergy Climate Fund

Table 4. List of European fusion start ups as December 2025. Data provide is indicative but not exhaustive.

This fragmentation limits Europe’s ability to align funding, regulation, and industrial strategy[38]. Geopolitical consequence is a growing risk of scientific leadership without industrial sovereignty.

Japan and South Korea: Key capabilities in the supply chain

Japan and South Korea exert influence in fusion development less through system integration than through dominance of enabling technologies. Both countries possess world-leading capabilities in superconductors, precision manufacturing, and advanced materials—capabilities that are indispensable to any fusion architecture.

[38] A Fusion Engine for Growth: A European Industrial Strategy for Fusion Energy, https://www.catf.us/resource/fusion-engine-growth-european-industrial-strategy-fusion-energy/.

Japan's annual public fusion spending is estimated at USD 400–500 million, supporting devices such as JT-60SA and extensive materials research. Japanese firms dominate segments of the high-temperature superconductor supply chain and ultra-precise components, positioning the country as a critical supplier regardless of which fusion concept prevails. This supply-chain leverage constitutes a form of strategic power that does not require ownership of full reactor systems.

South Korea follows a similar pattern. With annual fusion-related investment of approximately USD 300–400 million, centered on KSTAR and industrial R&D, Korea integrates fusion development into its broader advanced manufacturing strategy. Large business conglomerates participation ensures rapid translation of research into producible components, reinforcing Korea's role as an indispensable manufacturing partner.

Other actors, including Switzerland and Italy, occupy niche positions in vacuum technology, cryogenics, and diagnostics.

Region / Country	Annual Public Fusion Funding (approx.)	Cumulative Public Commitments	Private Fusion Investment (cumulative)	Dominant Funding Model	Strategic Implications
United States	**$0.8–1.5 bn / year** (high volatility)	~$25–30 bn historical (incl. labs)	**$8–9 bn** (≈50–55% of global private capital)	Federal R&D + VC-backed startups	Industrial leadership, rapid iteration, strong IP capture but vulnerable to federal budget swings
China	**$1.2–1.7 bn / year** (stable)	~$20–25 bn (est.)	**$4–5 bn** (mostly state-linked)	State-directed public programs	Long-term sovereignty, infrastructure depth, slower but resilient progress
European Union (EU-27)	**€0.8–1.0 bn / year** (ITER + R&D)	**€45–50 bn** (ITER lifecycle)	**€1.0–1.5 bn**	Public megaprojects, limited VC	Scientific leadership, weak industrial capture risk
United Kingdom	**£250–400 m / year**	£2–3 bn (incl. STEP program)	**£700 m–1 bn**	Hybrid public + private	Europe's most commercialization-oriented fusion policy

Japan	**$300–500 m / year**	~$6–8 bn	<$500 m	Public R&D + industry supply chains	Supply-chain leverage (magnets, materials)
South Korea	**$200–400 m / year**	~$4–6 bn	<$300 m	Public R&D	Manufacturing and component leadership
France (national)	~€250–350 m / year	Included in ITER total	<€300 m	Public nuclear institutions	Engineering depth, weak private fusion sector
Germany	~€200–300 m / year	~$2–3 bn	€300–500 m	Public science + startups	Stellarator leadership, unclear commercialization path
Canada	<$100 m / year	~$0.5–1 bn	**$500–700 m**	Private-led (General Fusion)	Startup-driven niche leadership
Australia	<$50 m / year	<$500 m	<$200 m	Research-focused	Materials, mining, niche science
UAE / Middle East	<$50 m / year	<$500 m	<$200 m	Strategic investment / hosting	Geopolitical positioning, not tech leadership

Table 5. Summary of Fusion investments and business/government approach per country

Appendix: 1. What is Fusion Power?

The possibility of obtaining energy from nuclear fusion reactions was first raised in the 1920s. In 1926, the British astrophysicist Arthur Eddington suggested that the processes responsible for the enormous energy emitted by stars must be linked to the fusion of light nuclei into heavier ones. This hypothesis opened a new field of research that encouraged scientists from different countries to study both nuclear physics and the mechanisms that govern stellar interiors, laying the foundations of fusion as an energy source.

The first experimental step towards reproducing these processes on Earth was taken in 1932 at the University of Cambridge. Ernest Rutherford and his team managed to induce fusion reactions in the laboratory, observing the interaction between deuterium nuclei. These experiments not only confirmed the possibility of merging light nuclei but also allowed the identification of new nuclear products such as helium-3 and tritium. Rutherford underscored that, although each fusion event released a significant amount of energy, the low probability of these reactions occurring implied a negative overall energy balance.

A few years later, in 1938, Hans Bethe developed a detailed theoretical framework to describe the nuclear reactions responsible for energy production in stars. By calculating the interaction probabilities of different reactions, Bethe proved that stellar energy comes from a complex chain of fusion processes that, over time, transform hydrogen into helium and subsequently into heavier nuclei. This work conclusively verified fusion as the fundamental mechanism of energy of the observable universe.

In the early 1950s, the accumulated knowledge on the physics of light nuclei fusion allowed the development of quantitative criteria to evaluate its viability as an energy source in terrestrial devices. In this context, John Lawson established the well-known Lawson criterion, which defines the minimum conditions necessary to obtain net energy in a confinement fusion system. These conditions depend on the plasma temperature, the density of particles, and the time during which the energy remains confined. Thus, the temperature to be reached by that machine had to be about 10 keV (100 million degrees Celsius), with an electron density of $n_e \sim 10^{20}$ m^{-3} and a confinement time of $\tau_E >$ 1.5 s. Reaching the density was relatively easy. Temperature seemed to be a difficult task, but several methods have managed to reach and even exceed this value. However, the real challenge would be the confinement time of the energy.

During this period, researchers began exploring different experimental configurations to replicate fusion on Earth. In 1950, Soviet scientists Andrei Sakharov and Igor Tamm proposed the concept of the tokamak, a device based on the magnetic confinement of plasma in a toroidal shape. Soon after, in 1951, Lyman Spitzer presented the alternative concept of the stellarator in the United States. Although the stellarator initially attracted much scientific interest, the experimental advances led by Lev Artsimovich in the Soviet Union showed that the tokamak offered better performance in terms of confinement, which led to its widespread adoption. Temperatures on the order of the kiloelectronvolt were reached for the first time in those devices.

The 1950s were also marked by a change in the political context of fusion research. The 'Atoms for Peace' conferences, organised by the International Atomic Energy Agency in 1955 and 1958, promoted international cooperation in the peaceful use of nuclear energy. As a result, fusion research was officially declassified, facilitating scientific exchange and accelerating technological progress.

A major breakthrough occurred in 1968, when Soviet tokamaks simultaneously reached unprecedented high temperatures and confinement times. These results consolidated the tokamak as the dominant configuration in fusion research, a position it still holds today as the most advanced concept from an experimental perspective.

In the 1970s, it became clear that the development of fusion would require efforts on an international scale. In Europe, this conviction led to the design of the Joint European Torus (JET) in 1973. The construction of this facility, which would become the largest operational experiment in magnetic confinement, was completed in 1983 in the United Kingdom, where it achieved its first plasmas that same year and established a global benchmark in plasma physics.

At the same time, the idea of a truly global project to demonstrate the scientific and technological feasibility of fusion began to take shape. This initiative crystallised in 1985, during the Geneva summit between the superpowers, when the ITER project was formally proposed. After more than two decades of negotiations, ITER was established in France in 2007 with the aim of demonstrating the sustained production of fusion energy under conditions close to those of an industrial plant.

Meanwhile, national programs — especially in Europe, China, Japan, South Korea, the United Kingdom, and the United States — continued to make progress in key areas such as plasma physics, neutron-subjected materials, and related technologies. Since the 2010s, the emphasis has begun to shift gradually from scientific demonstration to commercial feasibility and pilot plant design.

The most recent results reinforce this perception. In 2021, JET set a new record by producing 59 megajoules of fusion energy, surpassing its own 1997 record. Soon after, in December 2022, the National Ignition Facility in the United States achieved for the first time a net energy gain in an inertial confinement fusion experiment, reaching a $Q_{scientific}$ factor (gain) greater than unity. These milestones do not yet entail a commercial application, but they do confirm that the fundamental physical principles are validated.

Currently, about 130 experimental fusion devices are in operation, construction, or in the planning phase worldwide, along with multiple demonstration plant designs and pilot reactors. This collection of advances places fusion in a critical transition: traditionally considered a long-term scientific aspiration, it is beginning to emerge as a technological option with real implications for energy systems.

Fusion reaction

A nuclear fusion reaction is a phenomenon in which two low-mass atomic nuclei fuse to form a higher-mass nucleus, a process that is accompanied by a significant release of energy. This mechanism contrasts with nuclear fission, in which heavy nuclei are fragmented into lighter ones to produce energy.

Nuclear fusion is governed by the strong nuclear force, the fundamental force that holds protons and neutrons together within the atomic nucleus. For two nuclei to merge, they must come close enough for this force to overcome the electrical repulsion between protons, which have a positive charge. At extremely small scales, strong nuclear force dominates electrostatic repulsion, allowing nuclei to merge.

The released energy in a fusion reaction has its origin in the mass difference. The nucleus resulting from the fusion has a slightly lower mass than the sum of the masses of the initial nuclei. This difference is transformed into energy in accordance with the principle of mass–energy equivalence formulated by Albert Einstein, expressed by the equation $E=mc2$.

In conceptual terms, various combinations of light nuclei can lead to fusion reactions with potential energy application. Hence, any of the reactions indicated in the following table could serve as a basis for the design of a fusion system for energy production, provided that the physical and technological conditions necessary for its control and use are met.

No.	Reaction	Products
1	D + T	^{4}He (3.5 MeV) + n (14.1 MeV)
2	D + D	T (1.01 MeV) + p (3.02 MeV) (50%)
		^{3}He (0.82 MeV) + n (2.45 MeV) (50%)
3	D + ^{3}He	^{4}He (3.6 MeV) + p (14.7 MeV)
4	T + T	^{4}He + 2 n + 11.3 MeV
5	^{3}He + ^{3}He	^{4}He + 2 p
6	^{3}He + T	^{4}He + p + n + 12.1 MeV (51%)
		^{4}He (4.8 MeV) + D (9.5 MeV) (43%)
		^{4}He (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV) (6%)

7	D + ^{6}Li	2 ^{4}He + 22.4 MeV
8	p + ^{6}Li	^{4}He (1.7 MeV) + ^{3}He (2.3 MeV)
9	^{3}He + ^{6}Li	2 ^{4}He + p + 16.9 MeV
10	p + ^{11}B	3 ^{3}He + 8.7 MeV

Table 1. Possible fusion reactions for energy production. Source: Fusion Physics, IAEA.

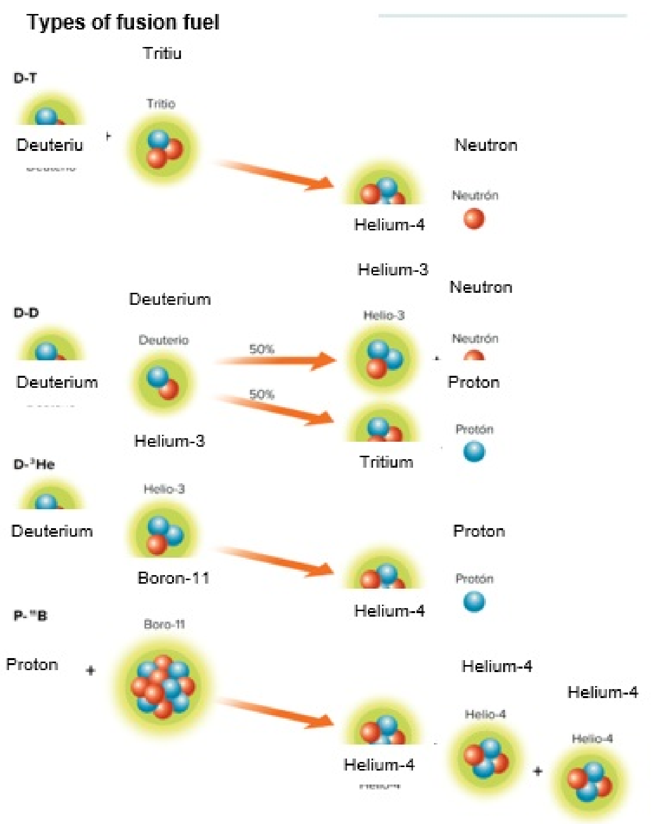

Figure. 1. Illustration of the fusion reactions mentioned in Table 1. Source: Infographic/Knowable.

The fusion reaction between deuterium and tritium (D–T) is the most widely used in current fusion device designs, as it presents the highest probability of reaction at relatively 'low' temperatures compared to other possible fuel combinations. Its cross section reaches a maximum around 100 keV, while other alternative reactions require significantly higher temperatures and, even so, have lower fusion probabilities. This difference explains why the vast majority of fusion reactor concepts under development rely on the D–T cycle.

As previously indicated, the energy feasibility of fusion is conditioned by the Lawson criterion, which establishes the minimum requirements for a fusion system to produce more energy than it consumes. This criterion acts as a fundamental reference for the design and evaluation of fusion machines, as it allows us to identify the physical limits that must be exceeded in order for fusion to become a useful energy source.

Lawson's criterion is structured around three key variables:

- Temperature (T): the plasma — an extremely hot ionised medium — must reach very high temperatures so that the fuel nuclei have enough kinetic energy to overcome their electrostatic repulsion and fuse.
- Density (n): the concentration of fuel ions in the plasma must be high enough to increase the frequency of collisions and, with it, the rate of fusion reactions.
- Energy confinement time (τ): the plasma must be confined at the required temperature and density for a sufficient time interval for the total number of reactions to generate a positive energy balance.

These three parameters are usually combined into a single parameter known as the Lawson triple product (nTτ), which serves as an indicator of the degree of proximity of a fusion experiment to energy balance and net gain. Achieving high values of this product entails a precise adjustment between heating, density, and confinement, which is one of the main scientific and technological challenges of fusion.

The ultimate goal is to bring the plasma up to the ignition regime, in which the energy released by the fusion reactions themselves is sufficient to compensate for energy losses, especially those due to radiation. At this point, the system can sustain the reaction without significant external inputs, marking the threshold towards a net production of fusion energy.

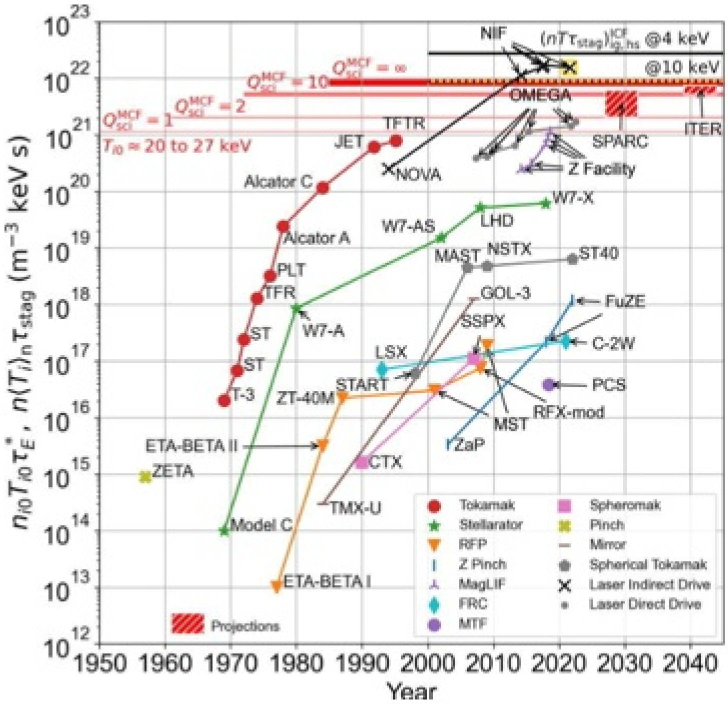

Figure 2. Advances towards the break-even point and fusion energy gain of different experimental fusion machines according to Lawson's criterion. Source: Phys. Plasmas 32, 112106 (2025).

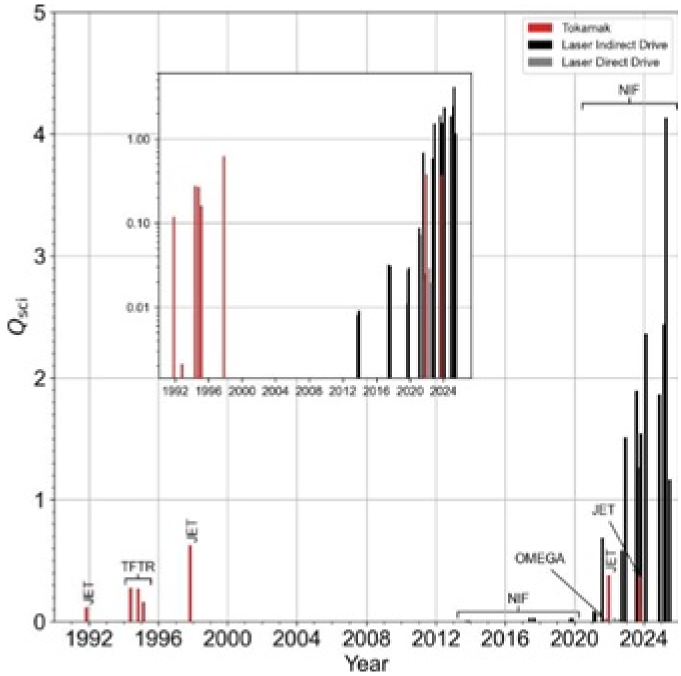

Figure 3. Graph of actual results versus date of D–T fusion experiments. Source: Phys. Plasmas 32, 112106 (2025).

Main technological approaches

There are currently multiple technological proposals aimed at obtaining energy through nuclear fusion. Although they differ significantly in their design and operating principles, they all share a common goal: to reach an operating regime capable of generating net energy in an efficient and controlled manner.

Most of these approaches rely on two major strategies for handling plasma, the medium in which fusion reactions occur. On the one hand, magnetic confinement systems use strong magnetic fields to contain and stabilise plasma at high temperatures. On the other hand, inertial confinement methods use extremely fast pulses via lasers or electric currents to compress the fuel to conditions where fusion can take place before the plasma expands.

There are also hybrid concepts that combine elements of both approaches, known as Magneto–Inertial Fusion, which seek to take advantage of each technique. To date, the greatest experimental milestones in terms of fusion energy produced have been achieved mainly in two types of devices: inertial confinement systems and tokamaks, which represent the most mature configuration within magnetic confinement.

From an experimental point of view, other alternatives are being developed alongside these main approaches. Though less advanced, they nevertheless present potentially attractive characteristics. These include concepts such as the Z-pinch, which, although still in early stages of development, continues to evolve and offer potential advantages in design simplicity or scalability.

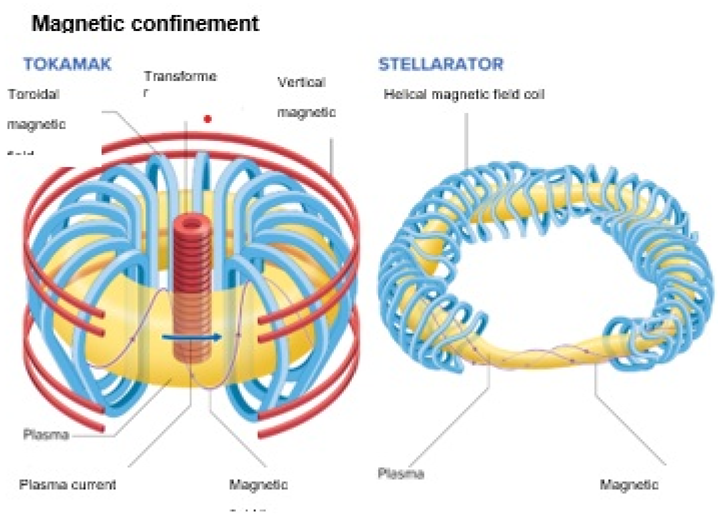

Figure 4. Magnetic confinement fusion machines: tokamak (left) and stellarator (right). Source: Infographic/Knowable.

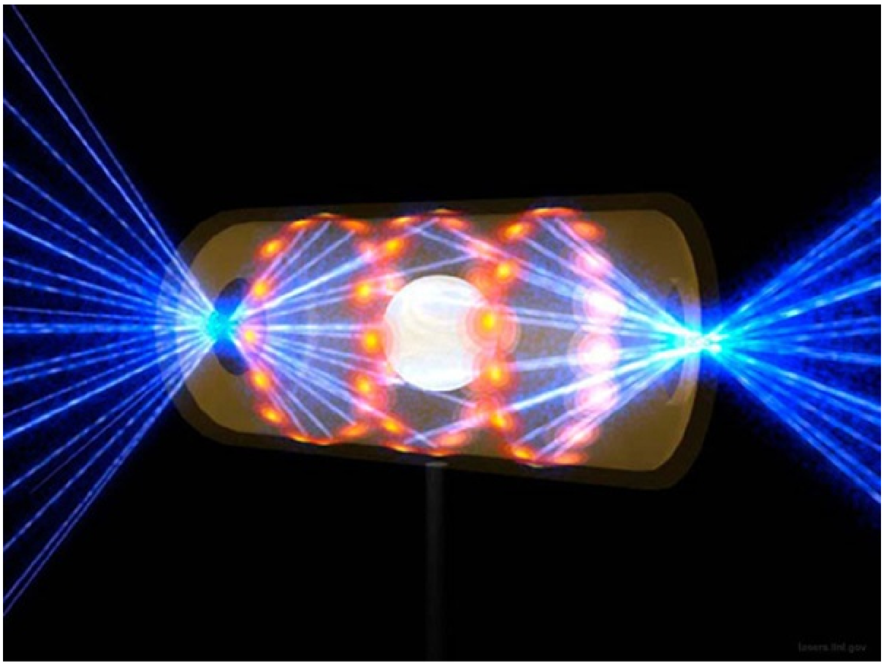

Figure 5. National Ignition Facility (USA). Experimental machine based on the concept of inertial fusion in which the installation's laser beams enter through the openings located at both ends of a hohlraum where the fusion fuel is located, in this case D-T. Source: Lawrence Livermore National Laboratory.

There are still major technical challenges that must be solved before fusion can become an operational energy source. The generation and control of plasmas subjected to extreme temperatures and pressures places very stringent demands on current technological systems. The difficulty of keeping the plasma stable for long periods and of limiting the energy losses associated with radiation and thermal transport processes are added factors that negatively impact the overall performance of the system. Likewise, the availability of materials capable of withstanding the intense neutron flux, high thermal loads, and mechanical stresses of a fusion reactor environment is a critical factor in ensuring its continued operation and long-term economic viability.

However, recent advances indicate that sustained progress is taking place. Improvements in magnetic confinement schemes, particularly in configurations such as tokamaks and stellarators, have increased both plasma stability and energy confinement times. In parallel, inertial confinement fusion, based on the rapid compression of the fuel by high-power laser systems, continues to show relevant results in the experimental field. Additionally, alternative fuel cycles are being explored, such as those based on proton and boron reactions — which, although presenting greater technological challenges, could lead to fusion reactions with reduced waste and potentially more favourable operational characteristics.

For a complete description of the physical principles that govern fusion energy and the technological implications that they entail, the following reference material is recommended:

- Principles Of Fusion Energy: An Introduction To Fusion Energy For Students Of Science And Engineering. A.A. Harms, D.R. Kingdon, K.F. Schoepf, G.H. Miley. ISBN-13: 978-9812380333.
- Fusion: Introduction to the Physics and Technology of Magnetic Confinement Fusion. Weston M. Stacey. ISBN-13: 978-0471880790.
- Fusion Physics. IAEA. https://wwwpub.iaea.org/MTCD/Publications/PDF/Pub1562_web.pdf
- Fundacion Innovacion Bankinter - Future Trends ForumEnergía de fusión https://www.fundacionbankinter.org/ftf-informes/fusionforward/

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