Fusion Energy: A Revolution in Progress

From Scientific Breakthrough to Industrial Deployment

fundación innovación bankinter.

Contents

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FUSION ENERGY AND THE GLOBAL ENERGY CHALLENGE: BUILDING A VIABLE INDUSTRY

Fusion Energy and the Global Energy Challenge: Building a Viable Industry

All forms of energy ultimately trace their origin to fusion. Solar, wind, hydro, even fossil fuels -each is a downstream expression of the fundamental reaction that powers the stars. If we can replicate here on Earth the same process that fuels the Sun, why keep relying on indirect energy sources? Fusion is the original engine of the universe. Its potential is vast: a clean, virtually limitless source of energy capable of reshaping our energy systems for generations to come. Imagine igniting a small star on Earth -one powerful enough to power our cities, industries, and homes well into the future.

But realizing that vision is no simple feat. Humanity stands at a critical energy crossroads. The climate crisis, surging global demand -driven by population growth, industrialization in the Global South, and the rapid expansion of electricity-intensive technologies like artificial intelligence- are stretching today's energy systems to their limits. Fossil fuels are fundamentally incompatible with global decarbonization goals. And while current solutions -renewables, energy efficiency, smart grids, energy storage, and nuclear fission- are vital, they alone are not enough.

In this context, **fusion energy** is emerging as a transformative strategic option: a clean, scalable, and reliable energy source with the potential to deliver massive baseload power. For the first time, fusion is no longer a distant promise. It is a rapidly evolving technological reality -scientific milestones have been reached, a new industrial ecosystem is beginning to take shape, and private investment is accelerating.We are at an inflection point. It is time to move beyond research and into deployment -to translate discovery into delivery, and innovation into infrastructure

1. What is Fusion Energy?

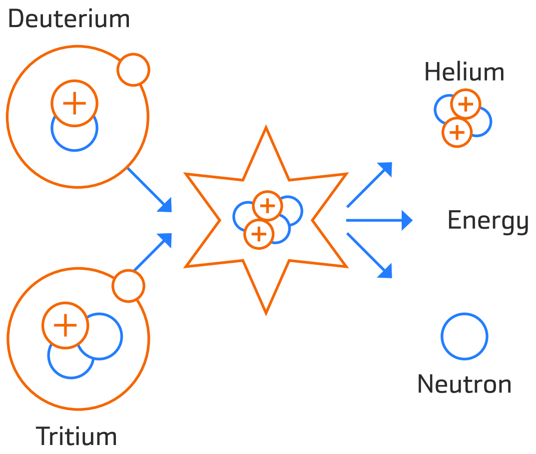
What is fusion?

Fusion is the process that powers the Sun: **combining two light hydrogen atoms** to form a heavier one (helium). In doing so, it releases an enormous amount of energy.

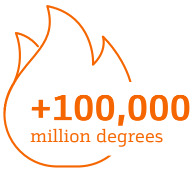
How does it work?

Fusion uses two special forms of hydrogen, known as isotopes

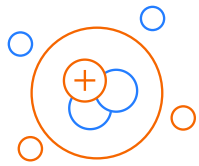
Deuterium, extracted from water.
Tritium, generated inside the fusion device itself using lithium.



2. The process

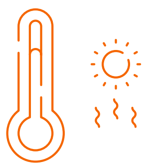


01. The fuel mixture is heated to over 100 million degrees Celsius (for reference, the Sun's core is 15 million)

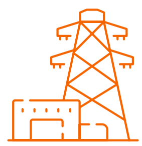


02. At this temperature, atoms turn into plasma, the fourth state of matter.

Plasma behaves like a gas, but it is so hot that its particles split into positive and negative charges (protons and electrons) moving freely.



03. Within the plasma, deuterium and tritium nuclei collide and fuse, releasing a tremendous amount of energy in the form of heat.



04. That heat is then used to generate electricity, much like in a conventional power plant.

The key difference: nothing is burned and no atoms are split -instead, they fuse together, and that fusion releases energy.

Why is it special?

No CO_2 emissions or long-lived radioactive waste.

Relies on abundant fuels -water and lithium.

A tiny amount of fuel can produce a massive amount of energy.

What are the challenges?

Keeping plasma stable is extremely complex.

Materials must withstand extreme temperatures.

Sufficient tritium must be bred to make the process self-sustaining.

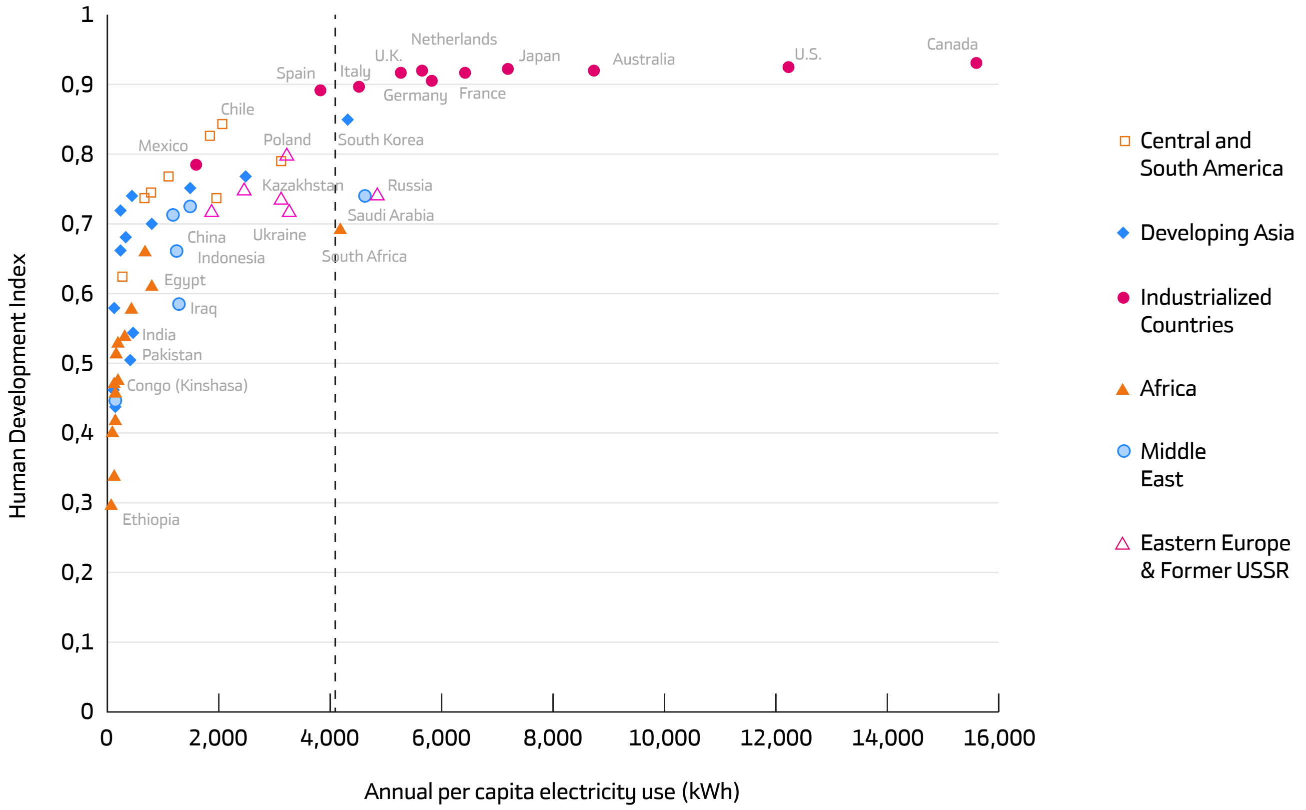
3. Different Approaches

Magnetic Confinement and Inertial Confinement

Detailed in chapter 2

The Energy Imperative of the 21st Century

The numbers speak for themselves. To ensure a decent quality of life for every person on the planet -based on Human Development Index standards- each individual would need access to at least 4,000 kilowatt-hours of electricity per year. Today, billions of people fall far short of that threshold. Assuming a global population of 10 billion by 2050 and an average per capita consumption of 4,000 kWh/year, global electricity demand would need to triple. This growth is not optional -it's a prerequisite for human development.



Yet despite decades of climate awareness, fossil fuels still dominate the global energy mix.

Between 2009 and 2019, their share declined by just 0.1%. Renewable energy is expanding, but it remains intermittent and dependent on costly backup infrastructure and storage systems. For example, Europe's electricity grids are not currently equipped to handle a 100% renewable mix without massive investment. Meanwhile, nuclear fission continues to face social resistance, unresolved waste challenges, and proliferation risks tied to weapons-grade materials.

From Promise to Pillar: The Strategic Role of Fusion

Fusion has the potential to become a cornerstone of a decarbonized, resilient energy mix -complementing renewables while progressively replacing fossil fuels. Its advantages are remarkable:

Extraordinary energy density	50 grams of lithium (from 280 liters of earth) and 12 grams of deuterium (from 400 liters of water) can generate the same energy as 300 tons of oil -the lifetime energy consumption of an average European citizen, according to Carlos Alejandre..
Zero emissions in operation	No CO_2, no long-lived radioactive waste, and no risk of nuclear proliferation.
Versatile applications	electricity generation, green hydrogen production, industrial heat, and neutron use in medicine and advanced materials.
Scalable and reliable	firm, predictable energy with a minimal land footprint.

As Carlos Alejaldre, Chair of the Fusion for Energy Governing Board and a leading international voice in the field, has stated: "Fusion can fully replace fossil fuels." Beyond its climate and energy value, **fusion represents an unprecedented industrial opportunity.**

The construction of ITER alone already involves ...

+ 2,000 European

companies working on advanced materials, components, and critical systems

+ €7,000 billion

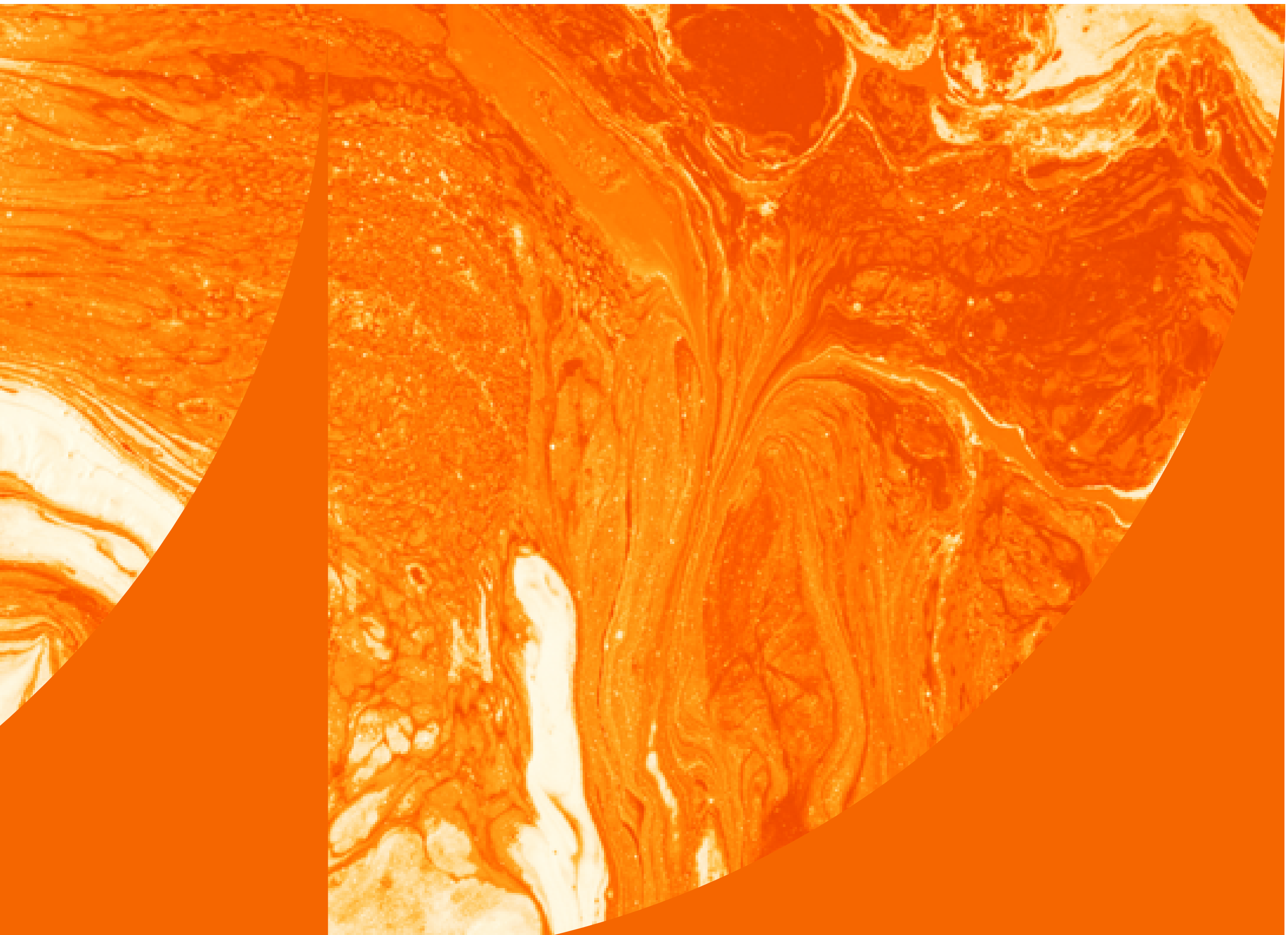
in awarded contracts

Source: https://fusionforenergy.europa.eu/wp-content/uploads/2025/06/F4E_Observatory_Report_1_Private_Sector.pdf

Building a robust supply chain for fusion is not only essential but could also become one of Europe's strategic industrial drivers in the coming decades.

This strategic vision of fusion as a key element in Europe's and the world's energy future is supported by studies such as "A systemic approach to the energy transition in Europe". The report underscores that achieving the Paris Agreement decarbonization goals will not be possible without fusion. It also calls for a systemic approach that integrates industrial, technological, and workforce capabilities -positioning Europe as a global leader, provided resources are mobilized now.

This opportunity is further highlighted in a recent **Clean Air Task Force** report on a European fusion strategy. Echoing the recommendations of the Draghi Report on European competitiveness, it outlines the roadmap for building a fusion energy sector capable of competing globally while simultaneously acting as a powerful engine of growth across the continent.



Accelerating the Future: From Science to Industry

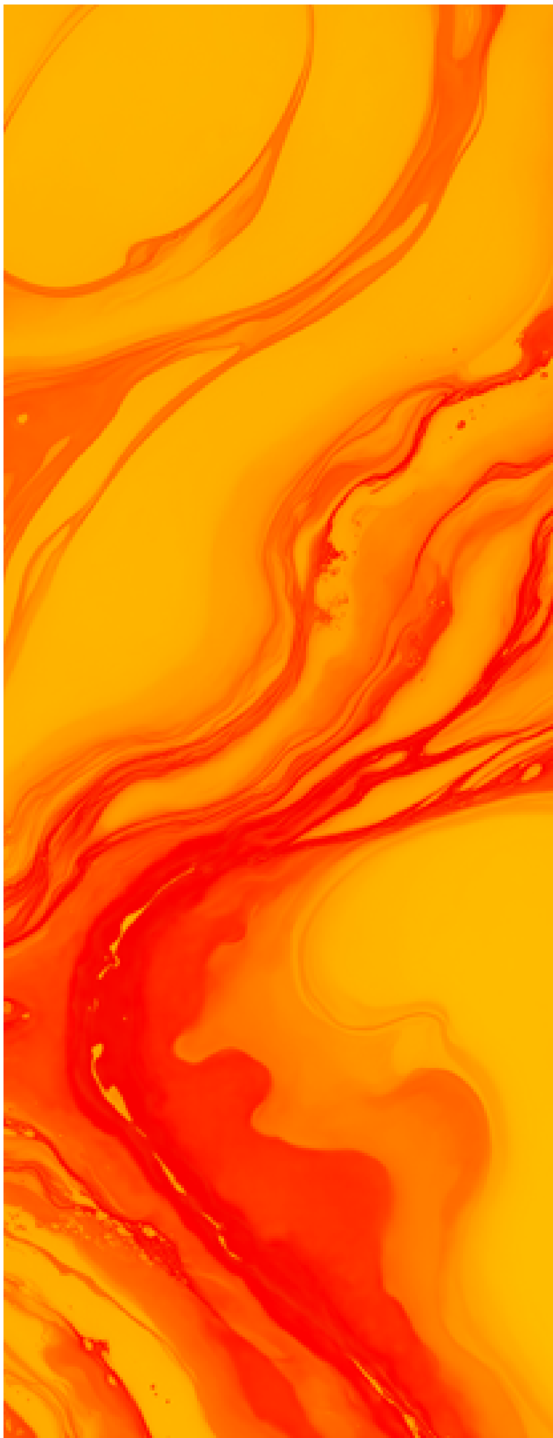
In recent years, spectacular scientific advances -combined with a surge in both public and private investment- have begun laying the foundations of a fusion energy industry. This joint effort is pushing fusion out of the laboratory and closer to commercial deployment:

1 NIF – United States

On December 5, 2022, the National Ignition Facility achieved scientific ignition for the first time -the moment when a fusion reaction generates more energy than is delivered to the fuel to initiate it. This milestone proved that a self-sustaining process is possible (3.15 MJ[1] produced from 2.05 MJ input, a gain[2] of ~1.5). Since then, multiple record-breaking shots have followed, culminating in April 2025 with a record gain of ~4.13 (8.6 MJ).

2 EU and UK

In 2022, the Joint European Torus (JET) set a world record by producing 59 MJ of fusion energy in a single pulse. Achieved through EU–UK collaboration, the result demonstrated that plasma can be kept stable for longer periods -a critical step toward commercial viability of tokamak devices.



[1] MJ: megajoule. One megajoule equals one million joules -or, to put it in perspective, roughly the amount of energy needed to boil about 3 liters of water.

[2] Gain (also known as the Q factor): measures how much energy is produced compared to the energy injected into the fuel. For example, a gain of 1.5 means the reaction generated 50% more energy than what was supplied.

3 ITER (Internacional)

The largest energy experiment in history, with seven global powers participating, is advancing toward operations. With a cost estimated between €18–20 billion, ITER will be the first device capable of producing sustained fusion energy greater than the power needed to maintain plasma confinement. It will also validate at scale key technologies such as magnetic confinement, heat extraction, and tritium breeding.

"ITER: The Largest Scientific–Industrial Collaboration in History"

€18,000–20,000 M

4 IFMIF-DONES (Spain)

A global landmark facility for testing and qualifying materials under intense radiation -an essential step toward building DEMO[3]. Located in Granada and led by Spain, the project has become a cornerstone of Europe's fusion technology ecosystem. In 2025, the European Commission approved €202 million through Fusion for Energy (F4E) for construction and commissioning of the particle accelerator -roughly 25% of the project's total cost.

[3] DEMO (por DEMOnstration Power Plant) es el siguiente gran paso en el desarrollo de la energía de fusión nuclear, y será el sucesor de ITER. DEMO será la primera planta de energía de fusión que generará electricidad, aunque aún no con fines comerciales. Su objetivo es demostrar que la fusión no solo es posible, sino también útil y sostenible a gran escala.

5 Private investment and venture capital

The private fusion sector has reached remarkable milestones. By mid-2024, it had raised over $7 billion. By June 30, 2025, the figure reached $10.74 billion in private funding alone. Notable examples include **Proxima Fusion's** €130 million round in Germany in June 2025, with co-founder **Lucio Milanese** -one of our forum participants- among its leaders. In August 2025, Commonwealth Fusion Systems (CFS) closed a Series B2 funding round worth approximately $863 million, bringing its total investment to nearly $3 billion -representing a significant share of the global capital deployed in private fusion companies.

As Carlos Alejaldre puts it: "**Plasma physics has done its job: we are now entering the technological era of fusion.**" The challenge is no longer to prove fusion works, but **to build real machines that can operate safely, competitively, and under sound regulation**.

This momentum toward industrialization must be both technological and organizational. A global ecosystem is beginning to take shape, bringing together public institutions, research centers, startups, major suppliers, and utilities. Strengthening this ecosystem will be crucial to accelerate development and build a resilient value chain capable of supporting a competitive, safe, and scalable fusion industry. This emerging industrial landscape will be analyzed in greater detail in the following chapters.

Despite these breakthroughs, fusion remains relatively unknown outside the fusion community. As **Richard Pearson**, who at the time of the forum in June was serving as CTO at **Kyoto Fusioneering**, observes: "When I talk about fusion with people in the business world, I realize they don't know what's happening."

Carlos Alejandre

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This lack of awareness can slow progress as much as any technical challenge. That is why clear communication of fusion's advances and potential is essential -to build the trust needed to attract investment, talent, and public support. This report was conceived to help society and policymakers grasp fusion's true potential.

The message is clear: the scientific threshold has been crossed. The time has come to move from words to action -to build a real, robust, and global industry around one of the greatest technological opportunities of our time.

The Need for a Strategic Vision for Fusion

Sehila González, Global Director for Fusion Energy at the Clean Air Task Force, emphasizes that fusion energy is no longer a distant promise but the outcome of 70 years of sustained scientific progress. Countering those who view today's momentum as a "bubble," she argues that the current landscape reflects a unique convergence of technological maturity, disruptive tools, and societal demand for firm, zero-carbon energy solutions.

González highlights that fusion meets the core requirements of the energy transition: it is carbon-free, firm, and scalable. She also underscores that the paradigm shift toward commercialization -driven by private-sector engagement- is transforming how scientists, engineers, and companies address the remaining challenges.

In her view, the challenge is no longer primarily technical; it is about decisions and action. With the tools now available, pilot plants can be deployed within this decade, paving the way for a fleet of operational fusion power plants on the grid before 2050. There are, she stresses, no excuses for failing to follow this path.

Her closing message is unequivocal: fusion is not a dream, it is a race we are already winning. But to cross the finish line, we need strategic vision, global collaboration, and decisive action today

Sehila González

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02

FUSION TECHNOLOGIES AND CROSS-SECTOR IMPACT

Fusion Technologies and Cross-Sector Impact

After exploring the global energy context and the transformative potential of fusion, it is time to turn to the technology itself.

Where do we really stand today? Which approaches are competing for leadership in this race? What breakthroughs have been achieved, and what challenges remain?

This chapter examines the state of the art in fusion technologies, their broader cross-sector impact, and the essential role of large-scale experimental projects in building a viable industry.

2.1 State of Fusion Technology Development

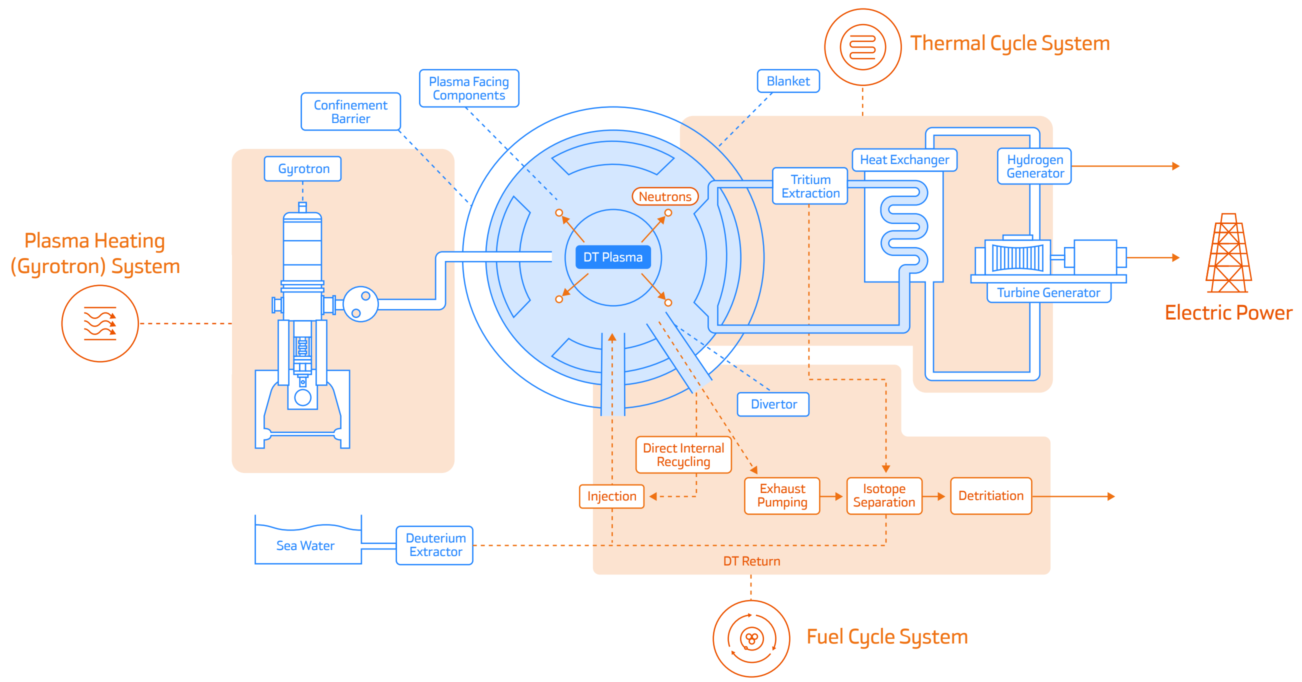
"Fusion is no longer a scientific challenge. It is an integrated engineering challenge".

With this blunt assessment, Gianfranco Federici, Program Director of the EUROfusion consortium, captured the paradigm shift underway in fusion energy. After decades of progress in plasma physics and experimental validation with devices such as JET (Joint European Torus, Europe's largest magnetic confinement experiment) and NIF (National Ignition Facility in the U.S., the world's leading inertial confinement facility), the challenge today is no longer about proving the science -it is about mastering design, reliability, and technological integration.

For **Federici**, moving toward an operational power plant requires more than producing energy in isolated bursts: it means building a complex system that can deliver electricity consistently, safely, and at competitive cost. He points to five interdependent technical barriers that must be solved in concert:

Kyoto Fussioneering Blog

The Fusion Era



Managing extreme heat

Plasma releases energy in highly concentrated zones, creating heat fluxes above 10 MW/m^2 -ten times hotter than the surface of the Sun. Designing and validating components such as the divertor[4] -the exhaust system that removes both heat and plasma impurities- capable of withstanding this stress over long cycles is one of the toughest engineering hurdles.

Neutron-resistant structural materials

The machine's walls will face relentless neutron bombardment. While advances in alloys and coatings have been made, no material has yet been fully qualified to maintain structural integrity under such extreme conditions.

Tritium production and control

Under the European DEMO model, a 1 GW fusion plant would require around 55 kilograms of tritium annually. Startups propose designs that could cut this demand to roughly 1 kilogram or less. But in every case, tritium must be bred inside the machine itself using breeding systems[5] -a technology not yet proven at industrial scale. To complicate matters, the first ignition of any device will require an external tritium supply, and current global reserves, already dwindling - the physical half-life of tritium is 12.33 years[6]-, amount to just a few dozen kilograms.

System-wide integration

All subsystems -plasma, materials, cooling, fuel cycle, remote maintenance- must function together seamlessly. Partial demonstrations are not enough. As Federici stresses: "Fusion cannot be validated piece by piece. We must prove that the entire system works as a whole."

Industrial scale-up

Moving from experimental prototypes like ITER to commercial power plants introduces new challenges in construction, remote operation, system availability, and cost reduction.

[4] Divertor: a critical subsystem of a fusion device designed to extract both the high heat loads and impurities from the plasma. It is among the most technically challenging components, as it must tolerate extreme thermal stresses and intense particle fluxes while ensuring plasma stability and material integrity.

[5] Breeding: In fusion energy, this refers to the process by which the fusion device itself produces the tritium it needs as fuel. To achieve this, materials such as lithium are placed around the fusion zone. When the neutrons generated by the fusion reaction strike the lithium, tritium is produced. This mechanism is critical, as there are no sufficient natural reserves of tritium in the world, meaning that fusion machines must generate it as they operate.

[6] Tritium takes a little over 12 years to decay to half of its original amount. As it decays, it transforms into helium-3 https://www.cnsc-ccsn.gc.ca/eng/resources/fact-sheets/tritium/

Federici also warns against the allure of "silver bullet" technologies. High-temperature superconductors (HTS), for example, hold great promise for more compact machines, but stronger magnetic fields also mean greater structural forces -a new set of engineering problems. "Integration changes everything. A technology may look promising on its own, but bring complications when built into the full system."

He emphasizes the urgent need for facilities such as IFMIF-DONES, where materials and components can be validated under realistic conditions before integration into a power plant.

Gianfranco Federici

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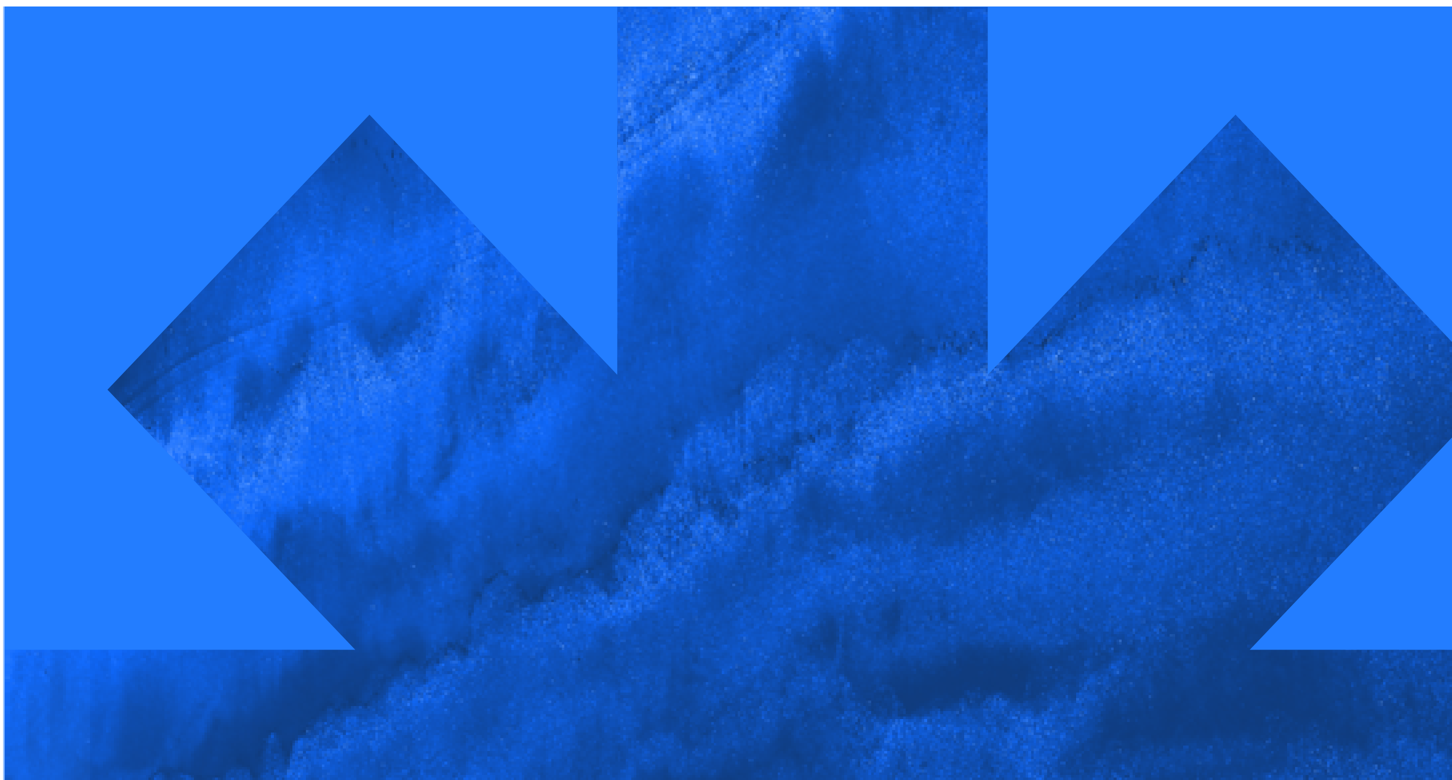
He also raises a stark warning: without rapid progress on new devices, the world's tritium reserves will run out. Above all, he calls for scientific honesty in the face of hype.

Fusion should be presented for what it truly is: a formidable but achievable technical challenge -provided there is long-term vision, industrial realism, and sustained investment.



Technological Competition: Multiple Pathways, One Common Goal

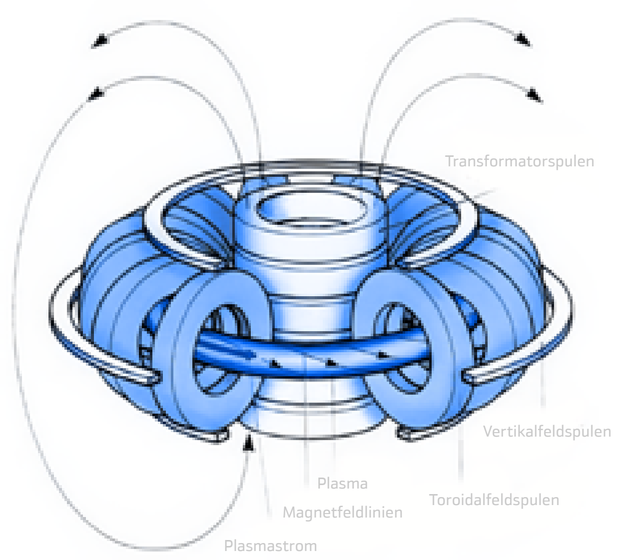
The development of fusion energy is organized around two main physical approaches: magnetic confinement, which stabilizes plasma with powerful magnetic fields, and inertial confinement, which relies on extremely concentrated bursts of energy to trigger fusion.

Both share the same fundamental challenge: **reaching temperatures above 100 million degrees Celsius** -hotter than the Sun's core- and **keeping the plasma burning long enough** for the reaction to generate more energy than is put in. This is the central difficulty: preventing the plasma, inherently unstable and prone to cooling or escaping, from extinguishing before it can deliver useful power.

From these two main approaches, several technological configurations have emerged, each with different levels of maturity, scalability, and commercial potential.

Magnetic Confinement

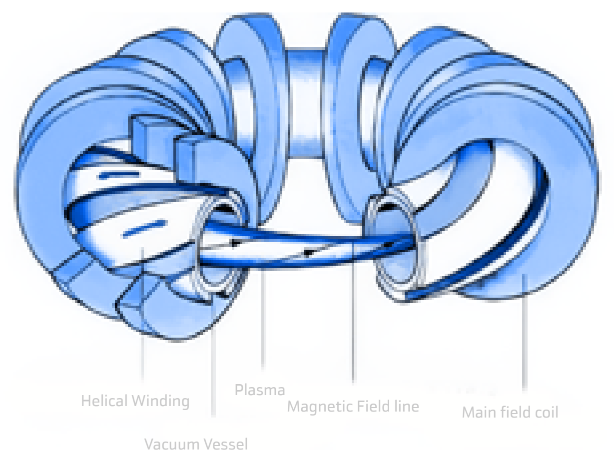
This approach keeps plasma hot and stable using magnetic fields that prevent it from touching the walls of the device. Tokamaks and stellarators are the leading configurations.



Tokamak

The most mature design and the foundation of major international projects such as ITER, JT-60SA and SPARC. It confines plasma in a ring-shaped torus with magnetic fields. Its strength lies in decades of operational experience, though challenges remain in controlling instabilities, enabling remote maintenance, and protecting against neutron bombardment.

Source: https://www.euronuclear.org/glossary/tokamak/



Stellarator

A helical, three-dimensional variant of magnetic confinement that can operate continuously without relying on induced plasma current. Historically harder to build and model, stellarators like Wendelstein 7-X are now proving long-duration stability and operational viability.

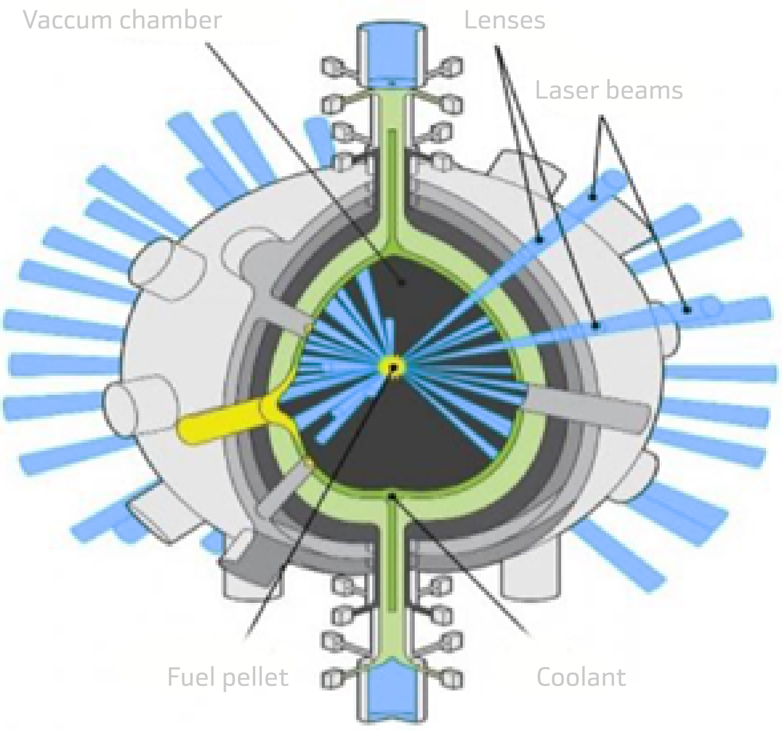
Source: https://www.euronuclear.org/glossary/stellarator/

Advanced configurations

These include spherical tokamaks (such as Spain's SMART, which is also based on a plasma configuration with negative triangularity) and Field-Reversed Configuration (IFRC). These variants aim for even higher efficiency in fusion machines, which in turn translates into lower final costs.

Inertial Confinement

This technique uses lasers or particle beams to compress a tiny fuel capsule with extreme intensity and speed, forcing nuclei to fuse before the capsule disintegrates.



Source: https://kdmengineering.com/blog/nuclear-fusion-power-future

Laser (ICF)

Uses powerful laser beams to compress and heat fuel capsules on incredibly short timescales. The National Ignition Facility (NIF, U.S.) landmark of achieving net energy gain has revitalized this pathway. Startups such as Xcimer, represented at our forum by its Vice President of Chamber and Plant Design, Susana Reyes, are pursuing more repeatable and economically viable versions.

Inertial–magnetic hybrids

Technologies such as Magnetized Target Fusion (MTF) combine magnetic fields with inertial compression. While still at early stages, they have attracted private investment for their potential compactness and modularity -for example, the Canadian company General Fusion.

In this context, Pablo Rodríguez, Principal Research Scientist and Group Leader at MIT's Plasma Science and Fusion Center, highlights that **tokamaks** remain by far the most studied technology, with over 50 currently operating and more than 100 built historically. Despite major progress, he stresses that no device has yet achieved a true burning plasma regime -a prerequisite for extrapolating to commercial plants. Achieving it is essential to resolve issues such as core-edge integration and validating divertor performance under reactor-scale conditions.

Rodríguez argues for the viability of compact designs based on high-temperature superconductors (HTS) and intensified magnetic fields, such as those developed under the SPARC project, in which he is actively involved.

These advances, he notes, could shorten innovation cycles and reduce costs. Yet he cautions that critical technical barriers remain -including divertor protection, impurity accumulation, and structural validation- that must be solved before scaling these designs. He also warns that many performance projections for future fusion devices still rely on empirical formulas derived from past machines.

New designs often fall outside the range where these formulas were validated. Rodríguez therefore advocates for **models grounded in plasma physics itself**, supported by advances in **computational simulation and artificial intelligence**, which are now making it increasingly possible to predict plasma behavior in the reactor core before construction.

"This is an exciting time for theory: for the first time, we can optimize machine design based on physics, not just extrapolation".

As an example of magnetic confinement innovation, Manuel García Muñoz, Professor at the University of Seville and Director of the Plasma Science and Fusion Technology Laboratory, presented the Fusion2Grid project, which aims to design the most compact and cost-effective fusion plant possible. The project is built on three technological pillars: spherical tokamaks, HTS magnets, and plasmas with negative triangularity -a configuration that reduces plasma–wall interactions and improves heat distribution.

The SMART device -a compact tokamak already operational in Seville- serves as a testbed for these solutions. **García Muñoz** emphasizes that this pathway allows faster development at lower cost and shorter timelines, without compromising performance expectations. At the same time, he underlines its challenges:

“There’s no magic here: every gain in compactness requires a complete redesign of the machine’s internal protection.” Space constraints force innovation in solenoid design, neutron shielding, and tritium breeding.

Turning to inertial confinement, **Susana Reyes (Xcimer)** sees NIF’s breakthrough as a turning point: for the first time, a fusion facility has repeatedly surpassed scientific ignition, achieving in April 2025 a net energy gain of 8.6 MJ from a 2 MJ laser pulse, with a scientific Q[7] = 4. This, she argues, closes the chapter of physical validation.

Reyes identifies two critical bottlenecks on the path to commercial inertial fusion:

- **Mass production of targets:** moving from highly specialized, expensive designs to formats that can be manufactured rapidly and cheaply. Today, NIF can only fire once every several hours; a commercial plant will need to operate at rates approaching one shot per second.
- **Repetitive, efficient, high-power lasers:** capable of reliably delivering multi-megajoule outputs at a cost point suitable for industrial deployment.

Manuel García Muñoz

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[7] Gain: also referred to as the Q factor. It indicates how much energy is produced relative to the energy injected into the fuel. For example, a gain of 1.5 means that 50% more energy was generated than was put in.

Xcimer is addressing this by developing a new **gas laser system (eXcimer)** that overcomes the limitations of solid-state lasers like those at NIF. This technology could reach energies of up to 10 MJ while cutting the cost per unit of energy by an estimated factor of 60, thanks to eliminating fragile and expensive optical components.

Its conceptual pilot plant design introduces several key improvements over previous configurations: only two laser beams (instead of NIF's 192), sub-1 Hz operation to ease chamber evacuation, use of a liquid wall (FLiBe) to protect solid structures and extend their lifetime, and an integrated system for breeding, heat extraction, and power generation.

Reyes underscores that this pathway is being developed in a fully civilian and open manner: "Civilian fusion designs do not rely on classified codes or military technology. We are building a purely commercial industrial ecosystem around this approach."

In this model, public–private collaboration is essential. Xcimer already partners with U.S. national laboratories such as Savannah River (tritium) and Oak Ridge (breeding blankets). The only potential military implications, she clarifies, come not from fusion itself but from the use of high-power lasers.

Moving from scientific achievement to industrial scale requires not just innovative engineering, but an integrated approach to design, manufacturing, operation, and maintenance. As Reyes concludes: "The story of NIF shows that when we persist with rigor and long-term vision, fusion delivers."

Susana Reyes

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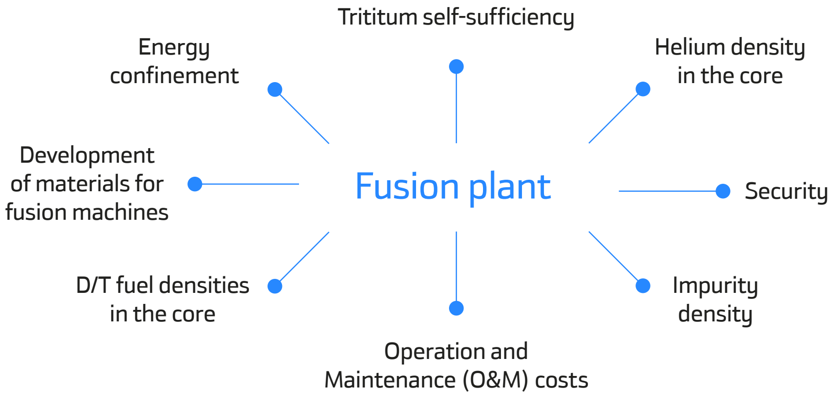
Modular Validation and a Systemic Approach

To properly assess the real maturity of fusion energy, Carlos Hidalgo, Director of the National Fusion Laboratory at CIEMAT, proposes a clear structural framework: a taxonomy of eight key dimensions that any viable fusion system concept must address in an integrated manner. These are divided into **four core physics challenges** -energy confinement, fuel density control (D/T), impurity management, and removal of residual helium- and **four essential technological challenges**- self-sufficient tritium breeding, development of radiation-resistant materials, maintenance and cost optimization, and operational safety management. We may have brilliant physics," **Hidalgo** warns, "but if the plasma heat flux damages the integrity of the fusion device's first wall materials or we are unable to manage impurity levels, the entire concept will fail. Effective integration of these scientific and technological criteria is the only true guarantee of viability."

Merger for society

Integration in a multi-dimensional space



Hidalgo advocates for a **modular validation strategy**, in which each subsystem is progressively tested under realistic conditions prior to full integration. This methodology allows for more agile and secure progress by anticipating potential technological bottlenecks without compromising the entire system. For instance, validating a breeding blanket module in an environment such as the one offered by **IFMIF-DONES** would enable industrial scalability without having to redesign every component of the fusion machine.

In the domain of magnetic confinement fusion, tokamaks remain the frontrunners for near-term pilot plants, owing to their demonstrated performance in current devices and the development of ITER. At the same time, optimized stellarators—intrinsically steady-state machines with built-in resilience to disruptions—are emerging as a robust alternative for the commercial deployment of fusion power.

Carlos Hidalgo

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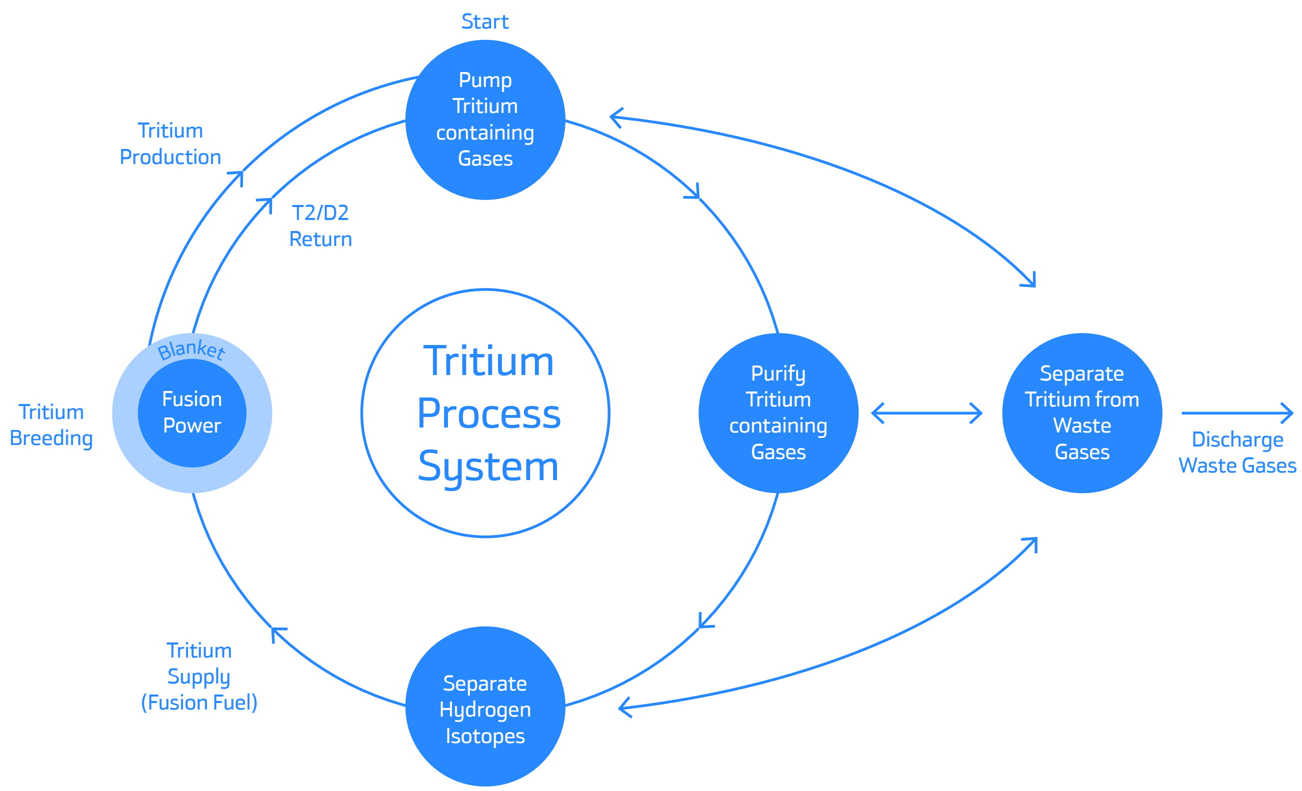
Materials and Tritium as Industrial Gatekeepers

Materials and fuel -especially tritium- are strategic factors that may ultimately determine the success or failure of fusion energy. Structural materials must withstand relentless high-energy neutron bombardment and extreme temperatures without degrading, while tritium -scarce and difficult to handle- is essential to sustain the reaction. Together, they define the design of fusion devices, their safety profile, costs, and industrial scalability.

As **Richard Pearson** (then representing Kyoto Fusioneering) underscores, tritium is “the elephant in the room.” It is not only scarce but its management directly impacts plant performance, safety, costs, and availability. “This isn’t something you can bolt on later. Tritium has to be at the center of the design from the very beginning,” he explains.



Source: https://www.srnl.gov/fact-sheets/fusion-fuel-cycle-research-and-development/

Tritium requires a fully integrated closed-loop system: from supply and storage, to isotope separation, extraction from the breeding blanket, and detritiation systems.

Each stage brings its own technical, operational, and regulatory hurdles.

The tritium cycle is a critical process that allows a fusion device to operate self-sufficiently

Richard Pearson

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1. Why is tritium important? The most feasible fusion reactions today use a mix of deuterium (D) and tritium (T), two isotopes of hydrogen. When D and T fuse, they produce helium, a neutron, and a large amount of energy. The challenge is that tritium is extremely scarce in nature: it has a short half-life (12 years) and is virtually nonexistent in free form.

2. Tritium production inside the fusion device (breeding): As reliance on external sources is not foreseen, a fusion reactor must generate its own tritium. This is achieved through the breeding blanket:

- The blanket surrounds the fusion plasma and contains lithium (either in liquid form or as lithium-based salts/fluids).
- Neutrons released from the D–T fusion reaction strike the lithium.
- These collisions convert lithium into new tritium through nuclear reactions.

3. Extraction and management of tritium: The tritium generated in the blanket is extracted through specialized systems that separate it from the lithium. It is then purified and safely stored, given its radioactive nature. The tritium is subsequently reinjected into the plasma as fuel.

4. Closed cycle: The goal is for the fusion reactor to be tritium self-sufficient -producing more tritium than it consumes. This is measured by the Tritium Breeding Ratio (TBR): the target is TBR > 1. If a reactor cannot breed enough tritium, it would have to rely on external reserves, which is unsustainable at scale.

5. Technical challenges:

- Designing blankets that generate sufficient tritium while withstanding extreme temperatures and radiation.
- Preventing leaks, since tritium is a radioactive gas that diffuses easily.
- Managing inventories to avoid fuel shortages.
- Integrating the tritium cycle with the rest of the reactor systems (plasma confinement, electricity generation, safety).

At the core of this cycle is the **breeding blanket**, tasked with producing tritium, dissipating heat, and shielding the machine's magnets. Klaus Hesch, Strategic Advisor at the Karlsruhe Institute of Technology (KIT), describes it as the "drivetrain" of fusion -the key system that transmits power. To date, no operational device has demonstrated an integrated breeding blanket, making its validation one of the central bottlenecks to fusion commercialization.

The technical and economic viability of fusion designs also hinges on **thermal efficiency**, which is directly linked to the coolant's operating temperature. Higher operating temperatures improve efficiency but impose tougher requirements on materials. This interdependence is critical for finalizing plant design and ensuring cost competitiveness.

The complexity grows when considering the wide range of **functional and structural materials** required. There is no single "silver bullet" material: more than twenty different types are expected to be necessary, from structural alloys and coatings to neutron multipliers and coolants.

Pearson summarizes it simply: "Everything in fusion is a materials challenge."

Klaus Hesch

Watch video

Validating these materials goes far beyond proving radiation resistance. Ángel Ibarra, Director of IFMIF-DONES Spain, stresses that the real test is durability under **true operational conditions**: "What matters is not just whether a material can survive radiation, but whether it can last through an entire operational cycle. That's the qualitative leap that will tell us what is viable and what isn't."

In this respect, **IFMIF-DONES** will be a one-of-a-kind facility worldwide. Its ability to generate neutron fluxes comparable to those in a working fusion reactor will allow qualification of materials, realistic simulation of operating conditions, and de-risking of plant design. As **Ibarra** notes, "One facility won't be enough -several IFMIF-DONES-type installations will be needed worldwide to gather all the necessary data."

Ángel Ibarra

Watch video

Finally, the tritium cycle raises not only technological but also **strategic and regulatory challenges**. Safety, traceability, availability, and fuel efficiency will determine not only plant viability but also public acceptance. All of this must be built into the design from the start, not added later.

Pearson's conclusion is clear: "If you don't integrate it from day one, you're doomed to redesign the system later."

Strategic Coordination: From Technical Creativity to Operational Convergence

As we have seen, technical divergence is real -and that is a good thing. Itxaso Ariza, Chief Technology Officer at Tokamak Energy and an expert in complex systems with a background in aerospace, reminds us that in emerging technologies like fusion, a diversity of approaches is not a weakness but a prerequisite for progress. What matters is how it is managed.

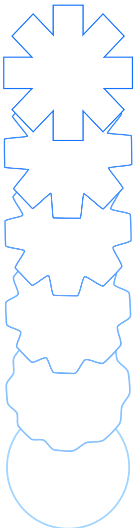
> “The less mature a technology is, the more important it becomes to combine different visions, hear every perspective, and then... disagree, commit, and move forward.”

Her proposal is clear: **technical divergence, strategic convergence.**

In practice, this means identifying two or three of the most promising technological pathways, backing them with aligned investment, and focusing efforts on validating them -while avoiding spreading resources too thin.Ariza also issues a critical warning: “The real challenge to fusion doesn’t lie within our community. It’s out there, among those who still don’t believe this is possible.”

Technological Gaps Setting the Pace for Fusion

The assessment from experts at the Future Trends Forum is clear: the critical subsystems for commercial fusion remain at **low technology readiness levels (TRLs)**, and their integration under real operating conditions stands out as one of the sector's greatest challenges -echoing the modular validation and systemic approach proposed by **Carlos Hidalgo (CIEMAT)**. This reality demands progressive validation strategies, testing each subsystem step by step before full integration.



TRL 9 Actual system "flight proven" through successful mission operations

TRL 8 Actual system completed and "flight qualified" througt test and demonstration (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5 Component and/or breadboard validation in relevant enviroment

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2 Technology concept and/or application formulated

TRL 1 Basic principles observed and reported

Key components such as the **breeding blanket (TRL 2)**, tritium handling, remote maintenance, and fusion-specific materials (TRL 3) are still in the experimental stage. Cross-cutting technologies like lithium enrichment or liquid coolants are currently at TRL 3–4 -still below the industrial threshold.

Only a few systems, such as plasma heating and tokamak divertors, have approached TRL 6, though they still require integrated validation under realistic neutron and thermal loads.

The launch of critical infrastructures such as **IFMIF-DONES,** along with new platforms for validating breeding blankets and tritium loops, represents a decisive step toward closing performance and integration gaps. These facilities will make it possible to test key components under representative fusion conditions -essential for advancing system readiness. Moreover, subsystem integration -which cannot be validated in isolation- requires a holistic approach from the earliest phases, given the technical and safety interdependencies involved

In short, accelerating the transition from today's TRLs is a prerequisite for moving toward viable fusion devices. Raising the technological maturity of these components is a necessary condition for fusion to enter its commercial deployment stage.

2.2 Technologies with Impact Beyond Fusion

Research in fusion energy is generating technologies with applications far beyond the sector itself. These so-called **spillover technologies** include next-generation superconductors, advanced cryogenics, specialized materials, and power electronics. Their impact extends into strategic industries such as medicine, transportation, aerospace, power grids, and scientific computing.

These technologies have emerged from the need to:

- Operate at extreme temperatures and manage very large magnetic fields.
- Ensure robustness and precision in highly complex systems.
- Develop new materials able to withstand radiation and critical environments.

To illustrate the scope of these fusion-driven innovations and their potential in other industries, the following section summarizes the main areas of development and some of their most relevant applications: Fusion Spillover Technologies and Their Potential Applications

Technology	Examples	Potential Applications
HTS superconductors	ReBCO, magnetic confinement magnets	MRI, particle accelerators, electric motors and generators, DC power grids
Advanced cryogenics	Cooling <30 K, superfluid helium	Space transportation, particle physics, industrial systems
Power electronics	High-power modular converters	Electrical grids, rail and electric transport, hydrogen production
Specialized materials	Liquid metals, neutron shielding, new steels	Advanced devices, aerospace, radiation protection
Robotics and remote maintenance	Systems developed for ITER and DEMO	Nuclear fission, defense, aerospace industry

Although these technologies originate in the scientific environment, they are already enabling applications far beyond the energy sector -from particle accelerators to medical imaging systems and electric propulsion. The path toward their industrialization is already underway.

Take superconducting magnets as an example. Their development, initially for facilities like the LHC particle accelerator, has enabled broader applications such as **magnetic resonance imaging (MRI)** and **nuclear magnetic resonance (NMR) spectroscopy**. Today, **the global MRI market exceeds $9 billion and is projected to reach $12 billion by 2030.**

As Frédéric Bordry, former Director of Accelerators and Technology at CERN and now CTO of Gauss Fusion, explains: "The history of high-energy physics and fusion shows that superconductors have enormous potential for technology transfer."

The current challenge lies in **industrial-scale production of HTS materials such as** ReBCO, which demand high manufacturing precision and face supply chain constraints. **Bordry** stresses the **urgency** of Europe developing its own production capacity, currently concentrated in China, Japan, and South Korea:

"Without an investment of €100–200 million, Europe will not be able to secure a sovereign supply chain in superconductivity."

On the **cryogenics** front, the stringent cooling requirements -traditionally below 4 K- have driven solutions now applied in major scientific facilities. Projects such as ITER and the LHC have established a robust industrial base for operating with **superfluid helium**, while new development pathways are targeting higher temperature ranges (20–30 K), reducing energy consumption and simplifying system design.

At the same time, the need for robust electrical systems to power magnets and manage reactive loads has spurred advances in **modular power converters**, with potential applications in electric transport, rail infrastructure, and distribution grids.

Frédérick Bordry

Watch video

A Case Study in Technology Transfer

Renaissance Fusion, one of the European startups featured at the forum, is transforming stellarator-related technologies into a platform with applications across multiple industries, explained by its Chief Operating Officer, Diego Cammarano.

The company is pioneering a novel method for fabricating superconducting coils -continuous, customizable, and far more cost-effective than traditional designs. This innovation radically simplifies assembly and paves the way for applications in electric motors, MRI systems, maglev trains, and direct-current power grids.

Beyond superconductors, Renaissance Fusion is advancing **liquid-metal systems** with uses ranging from neutron shielding and tritium production to thermal control in advanced fusion devices, including pressurized water reactors (PWRs). This ability to diversify illustrates how technologies born in fusion research can build entirely new value chains in energy, industry, and healthcare.

Cammarano also points out that even within the fusion ecosystem itself, there is room for **cross-pollination among competitors.**

Diego Cammarano

Watch video

"More than 24 startups are working with liquid lithium, and over 18 are developing their own HTS magnetic systems. There are real opportunities for collaboration -even among rivals."

Keys to Effective Technology Transfer

Technology transfer does not happen automatically. It requires:

Shared testing facilities
Where prototypes can evolve into industrial products.

Large-scale engineering capabilities
To help scale up complex systems.

Support from government institutions
As both funders and early adopters.

Partnerships with strategic sectors
such as medicine, defense, energy, aerospace, and particle physics.

As Frédéric Bordry puts it: “We must move from the lab to the system, and from the system to the plant. To get there, we need validation platforms, trained talent, and strong public–private collaboration.”

2.3 The Role of Experimental Projects

Large-scale experimental projects are essential for validating technologies, strengthening international cooperation, and training scientific and technical talent in fusion energy. Their value goes far beyond the physical results they deliver: they help build industrial capabilities, establish regulatory frameworks, and develop common standards for a future global industry.

01 ITER: Demonstrating Technical Feasibility

ITER is the world's largest fusion experiment. Its goal: to generate **500 MW of fusion power from 50 MW of input** -sustained for several minutes- without producing net electricity. This experimental facility is designed to validate essential fusion technologies such as superconducting magnets, plasma control, tritium handling, and heat exhaust. According to Alberto Loarte, Head of the **ITER** Science Division, more than 90% of components are manufactured off-site, within a truly unprecedented global industrial network. This model has required dedicated factories, bespoke standards for cleanliness and quality control, and engineering protocols closer to those of aerospace than of the traditional energy sector.

A critical lesson has been the importance of starting with complete, detailed designs: any modification during construction risks jeopardizing both schedule and budget. Another key learning has been the value of working closely with industry to align design requirements with manufacturing and integration realities -especially in **First-of-a-Kind (FOAK)** systems. The experience gained by European companies in ITER has created the world's most comprehensive fusion supply chain in Europe, one that today is already providing components to startups and fusion projects worldwide.

02 JET: A Pioneer of European Cooperation

Another landmark in Europe's fusion journey has been the Joint European Torus (JET), based in the United Kingdom. JET was the first facility to use deuterium–tritium plasmas and laid much of the scientific and technological groundwork now being transferred to ITER. Its value as both a testbed and a model of multinational scientific collaboration has been widely recognized.

03 JT-60SA and Japan–Europe Cooperation: Lessons in Integration

The JT-60SA **tokamak**, a collaboration between Europe and Japan, has enabled the validation of both magnetic confinement technologies and governance models for joint work between agencies and suppliers. As Shunsuke Ide, Deputy Director General of the Naka Fusion Institute at QST, explains, interoperability among partners was made possible by a "common technical language" -built on shared tools, coordinated CAD systems, and joint interface management.

Ide also stresses the **urgent need to establish fusion-specific codes and standards**, which do not yet exist, and to train technical leaders capable of coordinating the multiple subsystems that make up a fusion reactor. These competencies will be essential once industry takes the lead in building commercial plants.

04 IFMIF-DONES: Irradiation for Materials Validation

One of the most cited bottlenecks on the fusion roadmap is the validation of materials under neutron fluxes comparable to those in an operating fusion reactor. IFMIF-DONES, now under construction in Granada, Spain, will be critical in closing this gap. Using a high-intensity neutron source, it will enable testing of both structural and functional materials under realistic damage conditions.

Beyond material testing, **IFMIF-DONES** will serve as a central hub for component qualification, the creation of comprehensive materials databases, and the preparation of future regulatory licenses for demonstration plants such as DEMO. It is therefore a **strategic project for the entire international fusion community**.

05 NIF: The Inertial Benchmark

In the field of inertial fusion, the National Ignition Facility (NIF) in the United States has set a historic milestone by achieving, for the first time, **net energy gain (Q > 1)**. While its objectives differ from those of magnetic confinement machines, its symbolic and technological impact has been pivotal in reigniting global interest in fusion. NIF has demonstrated the physical validity of the process and opened the door to **new technological pathways now being pursued by private players.**

06 CIEMAT and Spain's Scientific and Industrial Base

CIEMAT, and in particular its National Fusion Laboratory -home to one of Spain's official Singular Scientific and Technical Infrastructures (ICTS)- has played a pivotal role in establishing a world-class fusion research community in Spain.

This multidisciplinary community spans fusion engineering and technologies as well as both theoretical and experimental plasma physics. It has also fostered the development of industrial consortia that participate in major international contracts, ranging from cryogenic systems to advanced diagnostic instrumentation.

The National Fusion Laboratory designed, built, and operates the TJ-II stellarator, a uniquely configured magnetic confinement device whose diagnostic capabilities enable in-depth exploration of fundamental plasma behavior. Recently, CIEMAT, in collaboration with IBM and aggity, has implemented generative AI technologies in the operation of TJ-II. This initiative applies tools like IBM watsonx to accelerate data analysis by identifying signal and image patterns, building predictive models, and even creating a virtual assistant to recommend experimental configurations and generate automated operational reports. The project forms part of the broader EUROfusion framework.

Beyond its domestic infrastructure, **CIEMAT** actively contributes to experimental programs on both tokamaks and stellarators in the EU, the US, and Japan. It plays a key role in systems engineering for **ITER**, has been instrumental in the design of **IFMIF-DONES**, and leads integrated science-and-technology efforts critical for advancing future fusion systems based on the stellarator concept.

Spain has also developed cutting-edge infrastructures such as the Centro de Láseres Pulsados (CLPU), which holds the capacity to support technologies related to inertial confinement fusion, should the country choose to pursue that path. New initiatives are gaining momentum as well -such as SMART **tokamak**, the only operational tokamak in Spain and one of the few active in Europe- which seeks to position itself in the development of compact, scalable, and commercially oriented fusion devices.

The location of **IFMIF-DONES** in Granada presents a strategic opportunity to cultivate a high-value fusion technology ecosystem, encompassing testing centers, innovation incubators, advanced training programs, and international investment attraction, as emphasized by its Director, **Ángel Ibarra**.

Talent development and technological sovereignty building

Beyond their scientific achievements, these projects serve as **training grounds for new technical talent**. They have trained thousands of engineers, physicists, welders, operators, and experts in vacuum systems and cryogenics, many of whom are now working in companies and research centers around the world.

As Shunsuke Ide notes, "The greatest value of JT-60SA is not only scientific but human: it is a factory of talent that will be essential to building the future of fusion." And as **Alberto Loarte** emphasizes, without dedicated standards, qualified professionals, and strong coordination structures, there will be no viable fusion industry.

Shunsuke Ide

Watch video

Alberto Loarte

Watch video

03 ACCELERATING THE COMMERCIAL DEPLOYMENT OF FUSION

Accelerating the Commercial Deployment of Fusion

Bringing fusion energy to market is not just about solving scientific challenges. It also requires building a robust industry, connecting to real markets, and doing so on competitive timelines.

This chapter explores the key factors needed to turn technological breakthroughs into a global, scalable industry, structured around four main pillars:

1.- **The supply chain** as the critical industrial bottleneck.

2.- **Enabling technologies** from other advanced sectors that can accelerate development.

3.- **The potential market for fusion**, extending well beyond electricity generation.

4.- **Deployment timelines**, both public and private, that will set the pace for market entry.

3.1 The Supply Chain: Fusion's Industrial Bottleneck

Turning fusion energy into a commercial reality requires **building -starting now- a supply chain that is strong, scalable, and reliable**. Experience from projects such as ITER has shown that the toughest challenges are found not only in laboratories but also in workshops, factories, and logistics networks.

As **Klaus Hesch (KIT)** makes clear: "Industrial maturity will not happen by accident -it must be designed from the start." He proposes **a dedicated industrial roadmap for fusion** built around three phases: mapping existing industrial capabilities, developing those that are still missing, and using the supply chain as a platform to learn, scale, and compete. **Hesch** stresses that many companies will not join the sector out of technical conviction alone -they need a credible market vision, sustainable contracts, and structured collaboration.

Miguel Ángel Carrera, founder and CEO of AVS, reinforces this point from his experience contributing to major projects such as **ITER, IFMIF-DONES**, and MITICA, alongside a long track record in related high-tech industries: "Designing is not enough. You have to build. And that requires an active, skilled, and diversified industry." From early prototypes to commercial plants, the supply chain must evolve in step with technological maturity while meeting regulatory requirements.

Carrera emphasizes that the industry needs to stay active and diversified as the fusion ecosystem develops. His approach is a **cross-sector strategy**, based on public–private collaboration, engagement across multiple industries, and designing systems that can evolve from R&D through to industrial production.

He also highlights **the need for long-term strategic alliances**, fusion-specific quality standards, and platforms that enable **technology transfer and open innovation**. As he puts it:

> "What you buy is something you've never bought before. What you design is something you've never designed before. Only trust can bridge that gap."

Bringing this vision into focus, David Zaragoza, Director of Fusion at IDOM, emphasizes: "The real challenge is not building a machine. It's building a fusion industry." IDOM has been involved in more than **170 fusion-related projects**, spanning both public initiatives (JET, ITER, DEMO, IFMIF-DONES) and private ventures. The company is also a founding partner of **Gauss Fusion**, underscoring its commitment to the industrialization of fusion beyond the role of a technical supplier.

Erik Fernández

Ver video

From both a long-term and historical perspective, Erik Fernández, CEO of the **Spanish Science Industry Association** (INEUSTAR), underscores: "The success of Spain's value chain has been built on 30 years of public–private collaboration with CIEMAT, and 15 years of joint work within INEUSTAR. A strong industrial association allows us to speak with one voice, build trust with the public sector, and share risks. It is a strategic tool, not just a lobbying group."

INEUSTAR represents an ecosystem that has evolved from manufacturing unique scientific components to operating in more industrialized production environments. According to Fernández, today's transition -from laboratory prototypes to competitive, scalable systems- requires new strategies: long-term alliances, market stability, and above all, a shared vision between science, industry, and institutions.

Examples such as **IDOM's participation in Gauss Fusion or AVS's diversification into sectors like space, synchrotrons, and accelerators** illustrate a new type of industrial player: cross-sectoral, resilient, and proactive. Fernández argues that this adaptive capacity must be consolidated within a stable framework of collaboration, one that includes testing platforms, mechanisms for co-developing technology, and a two-way flow of talent between public centers and private companies.

Miguel Ángel Carrera

Watch video

David Zaragoza

Watch video

Fernández identifies four critical factors that must be addressed now:

- Improved communication, both within the ecosystem and with society at large.
- Genuine trust-building between research centers and companies, overcoming differences in organizational culture.
- Guaranteed technological availability in sectors subject to demand spikes and fragile supply chains.
- Training highly skilled technical talent to sustain the sector's growth.

Bringing an international and innovation-driven perspective, **Itxaso Ariza (Tokamak Energy)** warns of the urgent need to make the fusion industry attractive to new players. With a hybrid background in technological innovation and industrial development, she stresses that the success of fusion will depend on building an **open, efficient, and competitive industrial ecosystem**. Many enabling technologies, she points out, already exist outside the fusion sector -in fields such as aerospace and aviation- and the key is to draw them into the fusion space intelligently.

"We need to lower the barriers to entry. We can't expect companies with critical capabilities to join on their own. They need reasons, support, and visibility."

Ariza outlines three lines of action:

1. Developing shared testing and certification platforms to accelerate industrial qualification.
2. Creating public–private investment schemes to spread technological risk.
3. Designing an ambitious narrative capable of attracting young talent and high-value companies.

She also highlights the importance of integrating high-tech SMEs with cross-cutting solutions, currently not on fusion's radar but essential to scaling the system. Ariza insists on the need to foster a product-oriented innovation environment with fast iteration cycles, clear standards, and global visibility.

"The challenge is not to build another ITER. The challenge is to build many machines - reliable, affordable, and produced at scale."

In short, the supply chain remains one of the main bottlenecks to scaling fusion. Overcoming it will require **industrial planning, active public policies, long-term strategic partnerships, and a compelling narrative** to mobilize talent, investment, and business commitment.

Itxaso Ariza

Watch video

3.2 Leveraging Enabling Technologies from Other Sectors

A strong supply chain alone will not be enough unless fusion also harnesses advanced technologies already proven in other high-tech industries. **Itxaso Ariza (Tokamak Energy)** emphasizes that many of these enabling technologies exist outside the fusion field -in aerospace, space, and automotive- and the real challenge is to bring them into the fusion ecosystem. She argues for lowering the barriers to entry for companies with critical expertise in **digitalization, advanced sensors, and automation** -areas not traditionally linked to fusion. The way forward, she notes, is to create **shared testing platforms, co-investment schemes, and clear industrial standards** that make it attractive and feasible for them to contribute.

Artificial intelligence **and digital simulation** are transforming the way fusion machines are designed and validated. **Pablo Rodríguez (MIT)** explains how recent advances in **first-principles physics models, GPU acceleration, and AI** are now making it possible to reliably predict plasma core performance. This qualitative leap opens the door to designs optimized directly from physics -rather than relying solely on empirical extrapolations.

Embodied AI -which combines artificial intelligence algorithms with robotics, advanced sensors, and autonomous systems- has been identified as a critical lever for **remote maintenance and inspection under extreme conditions**. Explored in depth in a previous edition of the Future Trends Forum, this approach enables the automation of complex tasks and ensures operational safety in environments where direct human intervention is impossible.

Experience from space exploration also provides valuable lessons. Charles Bolden, former NASA Administrator, Founder and CEO Emeritus of The Charles F. Bolden Group LLC, and Trustee of the Foundation, has argued for the need to design systems that can be operated and maintained remotely, drawing inspiration from the management of probes, satellites, and space stations. Such solutions are crucial to addressing the maintenance challenges of fusion machines without direct human intervention.

Another concept frequently highlighted by experts is the use of **digital twins** as a key tool for design validation and operational planning.

Miguel Ángel Carrera (AVS) stresses the importance of “designing from the screen” -using simulated environments that replicate real operating conditions before physical manufacturing. This approach reduces costs, anticipates problems, and accelerates technological iteration.

From a complementary perspective, **Frédérick Bordry (Gauss Fusion)** highlights how fusion can leverage decades of accumulated innovation in particle accelerators. Areas such as cryogenics, beam control, ultra-high vacuum, and high-precision instrumentation are shared challenges, already addressed in projects like the LHC. He also points to CERN's management model as a reference for running complex scientific infrastructures that aspire to evolve into industries.

Finally, nuclear fission also provides valuable lessons. **Miguel Ángel Carrera** stresses that the culture of safety, remote operation, and modular systems developed in fission should be embedded from the start in fusion. The sector is not starting from zero -there is much to learn from industries that have already walked this path.

Taken together, the conclusion is clear: fusion does not need to invent everything from scratch. **Integrating external enabling technologies is essential** to accelerate deployment, cut costs, and strengthen industrial reliability.

Technology	Reference Sector	Application in Fusion
Artificial Intelligence (AI)	Data science, computational physics	Plasma performance prediction, design optimization, operational data analysis
Digital twins	Aerospace, automotive	Operational simulation, operations planning, pre-manufacturing testing
Embodied AI (physical AI)	Robotics, space, automation	Remote maintenance, inspection in hostile environments, autonomous operation
Additive manufacturing	Industry 4.0, automotive	Production of complex components, reduced assembly times
Digitalization of control systems	Nuclear, aerospace	Process automation, operational safety, real-time telemetry
Advanced project management	CERN, nuclear fission, large infrastructures	Technical coordination, modularity, quality control, scalability
Lessons from nuclear fission	Civil nuclear	Safety culture, modular design, remote operation, licensing frameworks

3.3 Building a Market for Fusion

Fusion energy is not just another product; it is a technology with the potential to **reconfigure the entire energy system and reshape the foundations of the global economy**. Its promise is so vast that, once a competitive fusion device becomes available, demand will be virtually unlimited.

The real question is not if there will be a market, but how to prepare for it. The key lies in organizing -starting today- the value chain, regulatory frameworks, investors, and potential users so that, when the first fusion device arrives, the industry can scale immediately.

Moreover, **electricity is only one of fusion's possible applications**. Experts agree that fusion could also provide high-temperature process heat -essential for industries such as steel, cement, and heavy chemicals, where direct electrification is not feasible. It also opens the door to large-scale **green hydrogen production**, whether through electrolysis or thermochemical processes. In addition, the supply of **fast neutron fluxes** could transform nuclear waste management, enable the production of medical isotopes, and drive the development of next-generation materials.

From a strategic perspective, experts in energy investment make a powerful observation:

> "With fusion, energy is no longer bound to the scarcity of natural resources."

This decoupling represents a revolution in the model of human development: it enables a world where energy is no longer a limiting factor for progress. Experts remind us of what was stated at the beginning of this report: if every person on the planet consumed electricity at the level of OECD countries, global demand would reach **25 terawatts -more than triple today's consumption**- something impossible to achieve with fossil fuels. With fusion, it becomes feasible. Fusion therefore also addresses a deeper aspiration: **global energy equity.**

This urgency is amplified by the emergence of **new sources of energy demand**. Experts point out that the rollout of artificial intelligence and high-performance computing alone could account for **10% of U.S. electricity consumption by 2035** -even before factoring in the massive electrification of transport, industry, and data centers. In his view, fusion is more than a climate solution; it is a **bet on sustainable abundance** -a global economy no longer constrained by energy resources, enabling everything else: development, innovation, equity, and stability.

Current estimates place the potential **global fusion market at more than €800 billion over the next 20 years**, depending on the pace of adoption, decarbonization policies, and the progress of competing technologies. But the real challenge is how to turn this expectation into **real, sustained demand**.

This is where the **supply chain** becomes critical. As discussed earlier, many industrial players still lack clarity on how their capabilities fit into this emerging industry. The link between **technology supply** -what startups and research centers are developing- and **market demand** -what industrial sectors actually need- must be organized far more effectively.

This requires coordination mechanisms that align technological roadmaps with industrial value chains. In practice, it means connecting real capabilities with specific use cases, clear regulatory frameworks, and viable business models. In short, the supply chain is the critical bridge between the ability to produce and the ability to serve a real market.

The growing role of **investors and regulators** (see Chapter 4) is also underscored. Most investment funds are looking for market clarity, technological visibility, and stable collaboration frameworks. Several speakers stressed that investors only mobilize when they see clear signals of technical viability and future demand. In this respect, regulators (see Chapter 5) can play a decisive role by establishing incentives, guarantees, and standards that lower the entry risk for private players.

Another recurring theme is the need for **more realistic narratives**. Instead of promising a grid powered 100% by fusion by 2035, the focus should be on **partial applications, intermediate markets, and parallel benefits**. From **industrial heat to tritium production to cryogenic cooling systems**, fusion already has multiple target markets. The challenge is to articulate them intelligently.

Ultimately, fusion does not need to wait for a market to appear -it will catalyze the creation of a new, massive market.

Its capacity to deliver abundant, clean energy, generate new energy vectors, and unlock industrial opportunities could transform the global economy.

If the ecosystem organizes itself now -aligning supply chains, regulators, investors, and end users-then the moment a working fusion device demonstrates viability, fusion will become **the single greatest driver of energy and industrial growth of our era.**

3.4 Fusion Development Timelines

The timeline for deploying fusion energy varies significantly depending on the technological approach and the type of actor involved. Broadly, three key stages can be distinguished:

1. **Prototypes:** experimental devices designed to demonstrate critical aspects of plasma physics and engineering.

2. **Pilot plants:** facilities aimed at producing net energy, validating full systems, and connecting to the grid.

3. **Commercial plants:** industrial-scale installations with continuous operation, competitive costs, and full regulatory compliance.

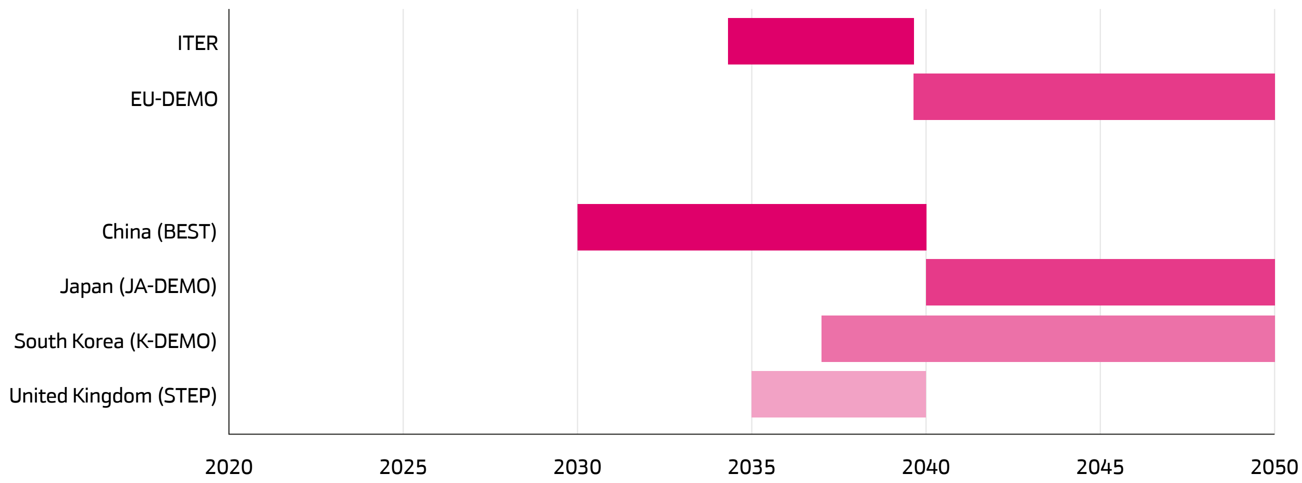
On the **public side**, where timelines are generally more conservative, **ITER** expects to begin plasma operations in **2034**, with deuterium–tritium fusion experiments around **2039**. From there, the pathway leads to EU-DEMO, ITER's successor, with ambitions to operate by around **2050**, generating between 3–4 GW of thermal power to prove both technical feasibility and tritium self-sufficiency. As for other **public initiatives worldwide**, notable examples include:

China Is building **BEST**, a machine designed to generate tritium as a precursor to CFETR, a DEMO-type reactor expected to consolidate its technology between **2030 and 2040**. These advances leverage the track record of the EAST project, the experimental tokamak in Hefei that has achieved world-leading plasma confinement milestones and now serves as a critical testbed de-risking technologies for next-generation facilities.

Japan is working on JA-DEMO, planned for the **2040s–2050s**, focused on stable generation of several hundred megawatts and tritium self-sufficiency -very similar in scope to EU-DEMO.

South Korea is developing K-DEMO, with its conceptual design launched in 2012, construction potentially beginning around **2037**, and grid connection projected for **2050**.

United Kingdom is advancing the STEP **project**, expected to achieve a self-sustaining plasma by **2035**. STEP aims to deliver net electricity from fusion by **2040**, with a planned output of **100 MWe** and in-situ tritium breeding.



Several other countries -including the United States, India, and Russia- also have national initiatives at various stages of development, often combining government programs with public–private partnerships.

Private-sector timelines, however, are far more ambitious. The startups represented at the forum are already setting milestones beginning in **2026**:

Tokamak Energy Plans to have its **ST80-HTS** device ready in **2026**, with its next pilot plant, **ST-E1**, designed to deliver electricity to the grid in the early 2030s.

Renaissance Fusion is advancing the development of **liquid-metal walls (lithium/ galinstan) for stellarators**, with laboratory prototypes in operation since 2023 and further technical milestones targeted through **2027**. These structures provide critical functions -neutron shielding, heat extraction, and tritium breeding- but do not themselves involve grid connection or direct energy demonstration phases.

Gauss Fusion projects an engineering phase from 2026–2032, followed by construction **between 2031–2038** and **initial operations between 2037–2044**. Its ambition is to become the first **1 GW grid-connected fusion plant** by the mid-2040s.

Xcimer Energy: Aims to validate its **Phoenix laser prototype** in **2026**, achieve net energy gain from its inertial device by **2030**, and launch its first commercial facility in **2035**.

Kyoto Fusioneering is preparing to launch its **UNITY 1 and UNITY 2** facilities in **2026**, essential for advancing tritium fuel-cycle and thermal technologies. Its goal is to support fusion pilot plants -planned for the late 2020s- with proven, integrated subsystems.

Proxima Fusion is progressing with its **Stellarator Model Coil (SMC)** demonstrator in **2027**, followed by the **Alpha prototype** in **2031**, designed to achieve net energy gain (Q > 1). The company aims to connect its first commercial plant to the grid sometime in the **2030s**.

And other leading startups worldwide are moving in the same direction:

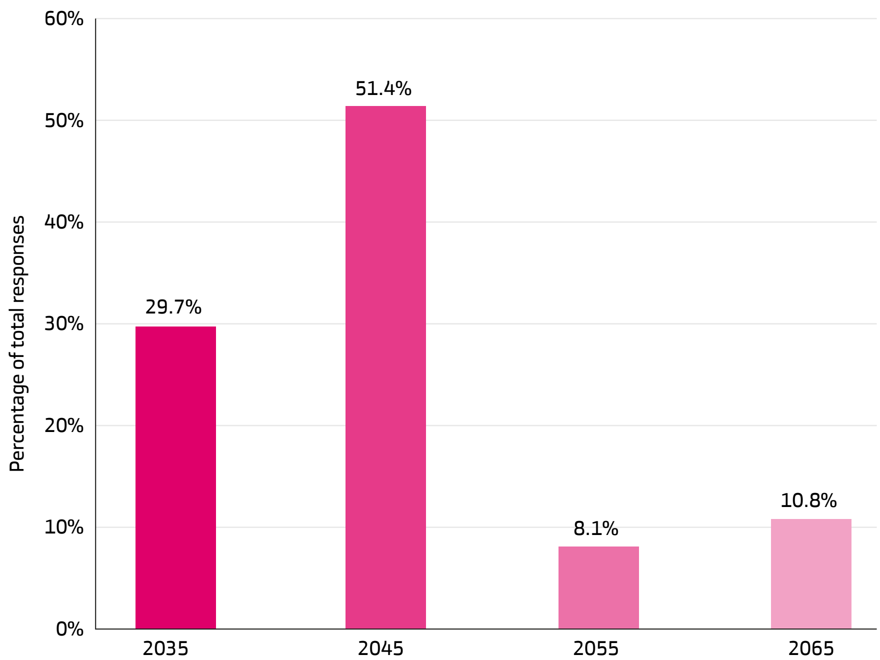
Commonwealth Fusion Systems (CFS) Is advancing the SPARC project, targeting first plasma in 2026 and net energy gain (Q > 1) in 2027. The next step is building the 400 MW ARC plant, expected to connect to the grid in the early 2030s.

Helion Energy Which has signed a supply agreement with Microsoft to deliver fusion power starting in 2028, aims to launch its Polaris machine that same year, providing direct electricity to the grid.

TAE Technologies Has already developed five demo units. Focused on hydrogen–boron fusion, TAE aims to have an operational prototype by the early 2030s, while also applying its fusion-derived technologies in adjacent sectors such as mobility and energy storage.

Taken together, these developments suggest that the **2030s will be a pivotal decade** for technological validation, with operating prototypes, first grid-connected systems, and quasi-commercial demonstrations. While the timelines are ambitious, they are supported by concrete progress in simulation, materials, lasers, and magnet technology, as detailed in earlier chapters.

The overall sentiment across the ecosystem reflects **cautious but growing optimism**. In response to the forum question -"By what year do you believe fusion will begin supplying electricity to the grid commercially?"- the results were revealing:



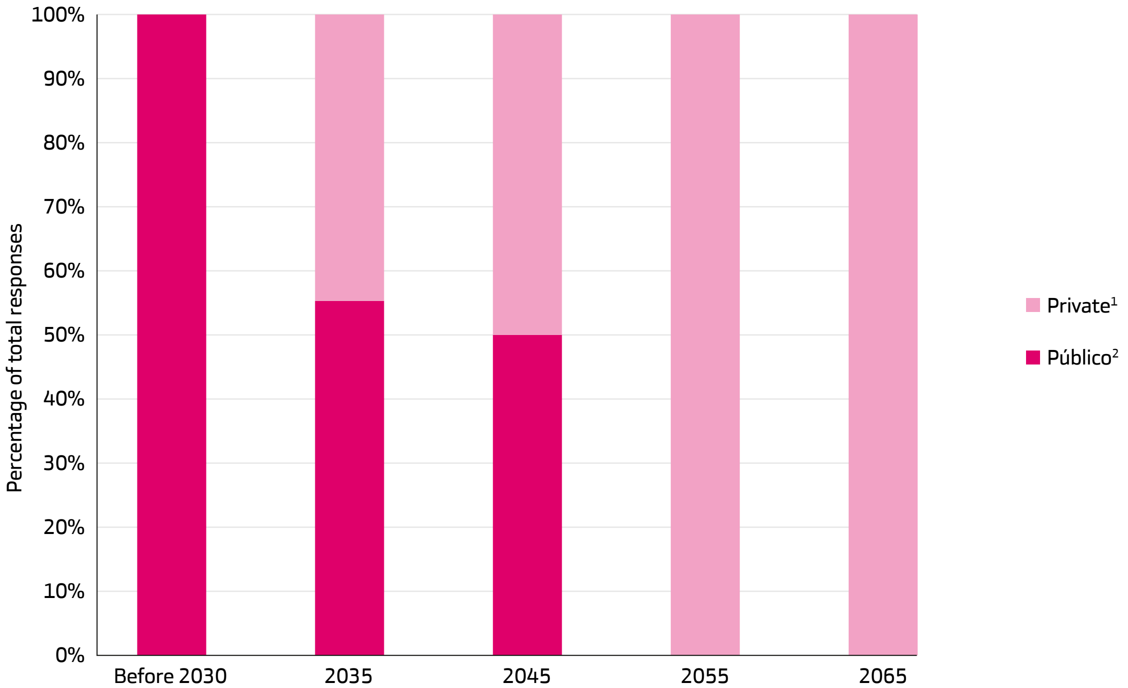
Source: analysis based on a survey of experts conducted at the forum.

More than 80% of experts believe that fusion could begin supplying power to the grid before 2045.

This contrast between public-sector horizons (beyond 2045) and private-sector ambitions (before 2035) for the first grid-connected pilot plant points toward **2040 as a realistic inflection point**. Overall, the data point to a firm expectation: between **2035 and 2045**, fusion could begin to integrate into the energy mix, at least through the first commercial-scale installations.

Importantly, fusion's arrival on the grid will not be a single event but a **progressive process**, with multiple intermediate demonstrators. What does seem clear is that the w**indow of opportunity is opening now**, and the next decade will be decisive in turning fusion's promise into industrial reality.

When asked -"When do you expect the first real pilot plant, meaning one capable of supplying electricity for at least ten hours?"- the experts responded as follows:



Source: analysis based on a survey of experts conducted at the forum

[8]Private sector: startups and corporations
[9]Public sector: national laboratories and public research institutes

04

FROM PUBLIC-PRIVATE PARTNERSHIPS TO INVESTMENT

From Public-Private Partnerships to Investment

Fusion energy is both an industrial challenge and a race toward successful execution. As discussed in earlier chapters, technological progress is accelerating and roadmaps are beginning to take shape. But no single actor can travel this path alone. The scale, complexity, and time horizon of fusion demand a **robust, dynamic, and effective model of public–private collaboration**.

In this new landscape, private capital -driven by growing confidence in technical viability- is playing an increasingly pivotal role. Fusion startups have attracted more than $7 billion in investment in less than a decade, while regulators are beginning to shape frameworks specific to this emerging sector. Yet **major gaps remain -in timelines, language, expectations, and risk models**.

This chapter explores how to bridge science, government, industry, and investment. Drawing lessons from collaboration models that have worked in other fields -such as aerospace- it identifies what makes a fusion project truly "investable" and highlights the critical factors needed to scale this technology with speed, rigor, and credibility.

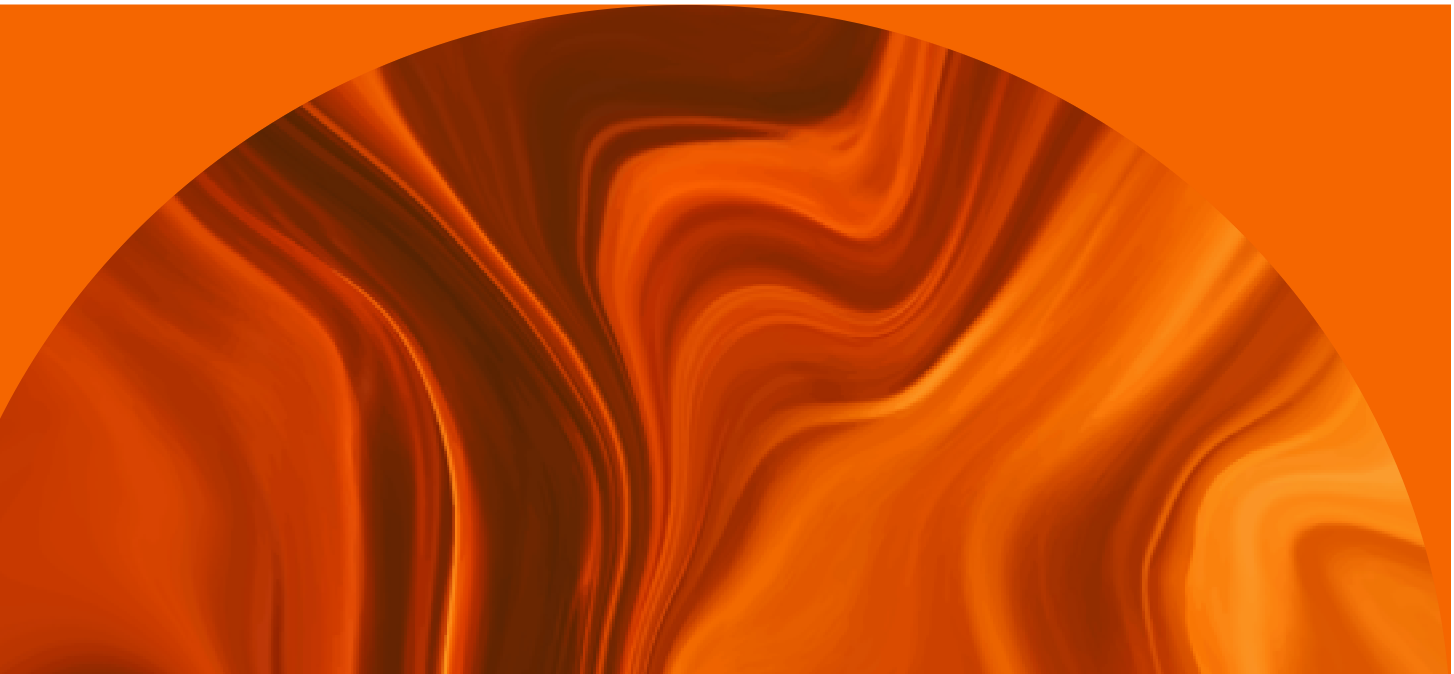
4.1 Public–Private Partnership Models

Public–Private Partnerships (PPPs) are emerging as a critical component in accelerating the deployment of fusion energy. As Carlos Alejandre (Fusion for Energy) emphasizes, without effective coordination between public institutions and private actors, it will be impossible to bridge the gap between basic research and commercial application. The public sector can contribute infrastructure, accumulated expertise, and institutional stability -taking on more risk in the early phases- while the private sector brings agility, technological innovation, and the ability to assume measured risks when it is time to scale.

María Teresa Domínguez

Watch video

In the same vein, María Teresa Domínguez, Head of Advanced Projects, R&D, and Nuclear Business at Empresarios Agrupados, stresses that the private sector is willing to invest in fusion, but it needs enabling conditions: regulatory certainty, market visibility, and early collaboration with scientific institutions. She underscores that the energy transition requires building an entirely new energy system -and that demands collaboration across all stakeholders.



Among experts, there is broad consensus: five key factors determine whether PPPs in fusion succeed:

Right timing

PPPs are most effective in the mid-stages of technological development (TRL 4–6), when there is already a solid scientific foundation and system-level validation is beginning. Move too early, and the effort risks being ill-timed; move too late, and it may become rigid or overly risk-averse.

Shared infrastructure

It is critical to leverage existing public facilities -such as rapid prototyping centers, materials testing lines, or advanced manufacturing environments- to support startups. This reduces costs and accelerates component maturity under real operating conditions.

Flexibility in intellectual property (IP)

IP should not be a barrier. Best practices recommend defining rights before the project begins, allowing companies to retain or license developments generated through collaboration.

Distributed testbeds

Multi-user platforms for validating components, testing tritium breeding systems, or trialing subsystem integration can lower entry barriers -especially for high-tech SMEs.

Integrated commercialization

Pathways for scaling to market must be built into PPPs from the start, not added as afterthoughts. This includes certification, regulatory support, customer validation, and planning for industrial rollout.

These principles are also evident in sectors such as **aerospace (NASA–SpaceX, discussed later)**, **semiconductors** (through programs like DARPA and consortia such as IMEC), and **biotechnology** (with companies like Moderna and BioNTech in their early phases). All of them have relied on public–private partnerships to achieve ambitious goals on shorter timelines and with greater efficiency.

The key lessons learned highlight that collaboration models must go far beyond ad-hoc subcontracting. They require **shared governance frameworks, common objectives, co-financing, and contractual structures that distribute technological risks.**

As Carlos Alejandre concludes: "Collaboration is not just desirable - it is essential if fusion is to become a reality."

Recommendations for scaling -developed in more detail in Chapter 7- point to the need for **stable collaboration platforms**, the combination of European, national, and private funding, and a stronger role for **industrial associations as strategic counterparts**. In short, if fusion is to reach the market, p**ublic-private collaboration is not optional -it is a fundamental condition for viability.**

Carlos Alejandre

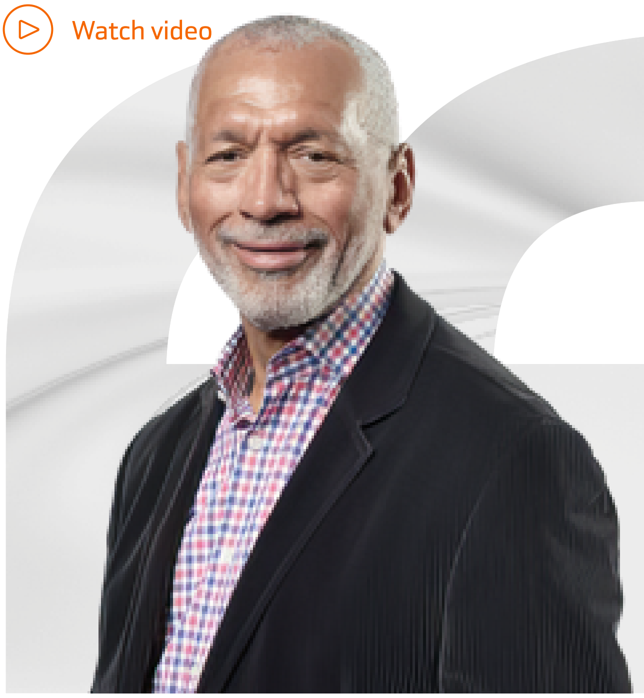
Watch video

4.2 Lessons from Other High-Tech Sectors

The development of fusion energy requires institutional coordination, industrial scale-up, public–private collaboration, and above all, a clear strategy to move from basic research to market deployment.

Charles Bolden

Watch video



The most frequently cited example at the forum was the **space sector**, particularly the collaboration model developed between **NASA** and private companies such as **SpaceX. Charles Bolden** (NASA and the Foundation) shared the keys to this transformation: when the agency decided to open up to private actors, it was not enough to simply transfer technology.

For two years, NASA brought together all the companies interested in commercial space to jointly review, adapt, and rebuild its safety, engineering, and certification standards. "We realized that many of our requirements made no sense for the new technologies. So we redefined them together. That allowed suppliers to do their job," explains Bolden.

This experience offers three critical lessons for fusion:

Smart regulatory flexibility:
It is not about lowering standards, but about adapting them to a new technological context. As **Alberto Loarte (ITER)** notes, applying rules designed for fission reactors to fusion devices can create inefficiencies and unnecessary costs. What matters is setting safety frameworks that are proportional, clear, and tailored to fusion.

Institutional–industrial co-design:
Bolden stresses the importance of involving future operators from the outset in shaping standards, processes, and objectives. This shared approach reduces misinterpretation, improves efficiency, and strengthens trust between the public and private sectors.

An inspiring strategic narrative:
The experience of the International Space Station -a massively complex international and political collaboration- shows that large-scale projects can be powerful catalysts for cooperation and global progress. As Bolden puts it: "International collaboration is a miracle when there is a common mission."

Another relevant case for the fusion industry is Airbus.

Its creation in the 1970s marked a strategic decision to share risks and pool capabilities at the European scale during a critical moment for the continent. Beyond its commercial success, Airbus provides valuable lessons: how to establish **common engineering, quality, and certification standards** to compete globally; how to build a pan-European value chain prepared to innovate and adapt to new markets; and how to foster a **culture of multinational management, negotiation, and adaptation**.

The **A380 experience** -a technological milestone that also revealed the complexities of cross-country integration- underscores the need for robust collaborative structures when handling advanced technologies. Like aviation in its time, **fusion requires a shared industrial architecture, long-term vision, and multinational governance**.

Beyond institutional collaboration frameworks, **financing mechanisms also provide relevan**t lessons. One of the most transformative is the milestone-based funding model.

Experts note that this approach, widely used in sectors like aerospace, has recently been adapted to fusion in the United States. Inspired by satellite programs of the 1960s and refined by NASA during the Apollo program, this model ties disbursements to **predefined technical milestones**, assessed by independent experts

At least **10% of the contract is withheld until the final phase**, incentivizing full project completion.

"The milestone-based funding model, applied in the space sector through NASA's COTS program, proved highly successful: SpaceX and Boeing received payments tied to concrete milestones, enabling innovation without compromising financial accountability."

This model was recently adapted by the **U.S. Department of Energy** under the Energy Act (2020) through a milestone-based program for grid-connected fusion prototypes. In 2023, $50 million was allocated to eight companies -including **Commonwealth Fusion Systems, Focused Energy, Tokamak Energy, and Xcimer**- leveraging more than **$350 million in additional private investment**.

- **Reducing risk** for emerging companies.
- Increasing private-sector participation.
- **Ensuring measurable progress** toward real prototypes.
- **Encouraging early negotiations** on intellectual property and data ownership.

Europe is also moving in this direction: initiatives such as GO4FUSION and programs under Euratom / Horizon Europe are introducing milestone-based schemes to attract private investment into early-stage projects -for example, Spain's RODAS project, which promotes component manufacturing in collaboration with SMEs and R&D centers.

In short, milestone-based funding is a powerful lever to link technological innovation with tangible progress toward industrially deployable solutions. It is, without doubt, a model that the fusion sector should continue to adopt and expand.

Experts such as **Itxaso Ariza** (Tokamak Energy) and **Miguel Ángel Carrera** (AVS) reinforce this view, calling for **more integrated management models, greater industrial involvement in project definition, and a communication strategy that inspires society**. As Carrera concludes: "If we believe fusion is the future, we need to start communicating it now -not only with data, but with stories that inspire and attract talent."

Adopting these lessons will accelerate fusion's rollout, making the sector more attractive to investors, regulators, and markets alike.

4.3 What Makes a Fusion Company Investable?

Investment in fusion energy has moved beyond a speculative exercise in technical futurism to become a concrete bet within venture capital portfolios -particularly in today's climate and geopolitical context. But what truly makes a fusion company investable?

Project Objectives: A Clear Vision and a Differentiated Value Proposition

One of the defining factors for whether a fusion project is investable is the **clarity of its strategic vision**. Investors look for teams that can articulate a realistic, measurable end goal and position their technology within a concrete market context. As experts put it: “The most promising companies aren't the ones that claim fusion will solve all the world's problems, but the ones that know what they can deliver -and to whom.”

That vision must be paired with a **clear and differentiated value proposition**. Rory Scott Russell, Managing Partner at East X Ventures, notes that successful startups identify a **“beachhead market”** early on -a first niche where they can prove value before scaling- and link their technology to real, unresolved problems in sectors such as power generation, industrial heat, hydrogen, or medical isotopes.

Rory Scott Russell

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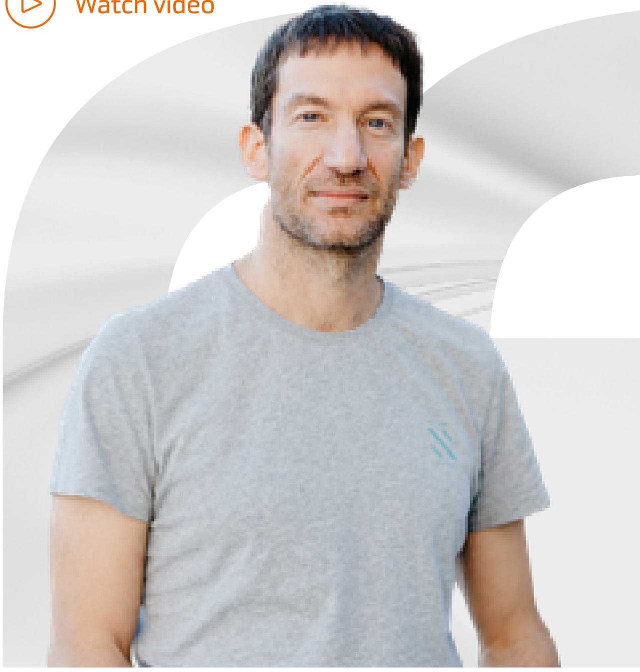
To be attractive, a company must show that beyond having a promising technology, it is built around a focused, concrete mission.

Eden Shochat

Watch video



That means answering fundamental questions with precision: What problem am I solving? Which sector am I targeting? How am I different? Why now?

In fusion, where many concepts are still far from commercialization, articulating a roadmap that bridges today's stage to a viable future product or service is essential for winning investor confidence.

Investors also place particular value on proposals that align their technological narrative with major social and climate challenges. A well-defined vision not only guides the internal team but also serves as a catalyst to attract talent, partnerships, and capital. As Eden Shochat, Partner at Aleph VC and Trustee of our Foundation, puts it, a compelling narrative can transform a complex scientific challenge into an opportunity the market can understand and embrace.

How to Structure a Fusion Project that Inspires Investors

The organizational structure of a fusion project is just as important as its technology. Investors scrutinize five key elements:

Strong, multidisciplinary leadership

The founding team must combine technical expertise with experience in management, regulation, and business development. According to **Rory Scott Russell**, the most compelling teams bring together plasma physicists, materials engineers, supply-chain experts, and managers with a track record in large, complex projects.

Clear governance models and strategies

A startup must demonstrate professional corporate governance, with structures such as boards, committees, and metrics for both technical and financial progress. Even if fusion projects are still under development, the organization must be prepared to scale, bring in external capital, and collaborate with public and private stakeholders. Investors demand clarity on **voting rights, intellectual property, and profit sharing**.

A technical roadmap with measurable milestones

A well-defined, realistic development plan is essential -one that specifies stages, timelines, associated costs, and assessed risks. Many fusion startups lose appeal because they fail to articulate their technical goals in a sequenced, verifiable way. Here, mechanisms such as **milestone-based funding or scalable prototypes** are critical to track progress and maintain credibility.

Industrial backing and strategic alliances

The project's structure should include partnerships with R&D centers, suppliers, corporate partners, or joint development platforms to accelerate component manufacturing, materials testing, and systems integration. Corporates are more inclined to support startups that demonstrate real technical cooperation rather than operating in isolation.

Ability to scale and diversify

While the primary focus is building a fusion power plant, investors value **technical transferability** -the ability to apply the technology in other areas along the way, such as industrial heat, medical isotopes, or control systems. This approach diversifies revenue streams and spreads technological risk.

In short: a project's structure must show that the team knows **what to build, how to build it, with whom, under what conditions, and where to scale next**. That comprehensive vision is what transforms a laboratory idea into an **attractive, credible, and financially viable business opportunity**.

Aligning Timelines: Bridging Investor and Developer Expectations

One of the main tensions in the fusion ecosystem lies in the mismatch of time horizons. While scientific and technological development in fusion typically requires 10–20 years of maturation, investors -especially venture capital funds- operate on much shorter cycles, generally 5–10 years.

Rory Scott Russell summarizes it clearly: "To be investable, a fusion project must show visibility of significant milestones within the first five years. Immediate returns aren't realistic, but technical traction and a credible roadmap are." This forces startups to design pathways that validate technologies, attract talent, and mobilize capital well before reaching the ultimate goal of a commercial plant.

From the investor's perspective, Eden Shochat notes that founding teams must prove they can learn, adapt, and execute quickly -even in long-term projects: "In venture capital, we don't invest in ideas. We invest in the team's ability to reach the finish line."

Experts add another critical point: for a fusion project to be financially viable, it must **clearly articulate its "windows of opportunity" before full commercialization**. These can include intermediate licenses, revenues in adjacent markets, or regulatory validations. The key is structuring innovation in stages that both reduce risk and align technical progress with financial expectations.

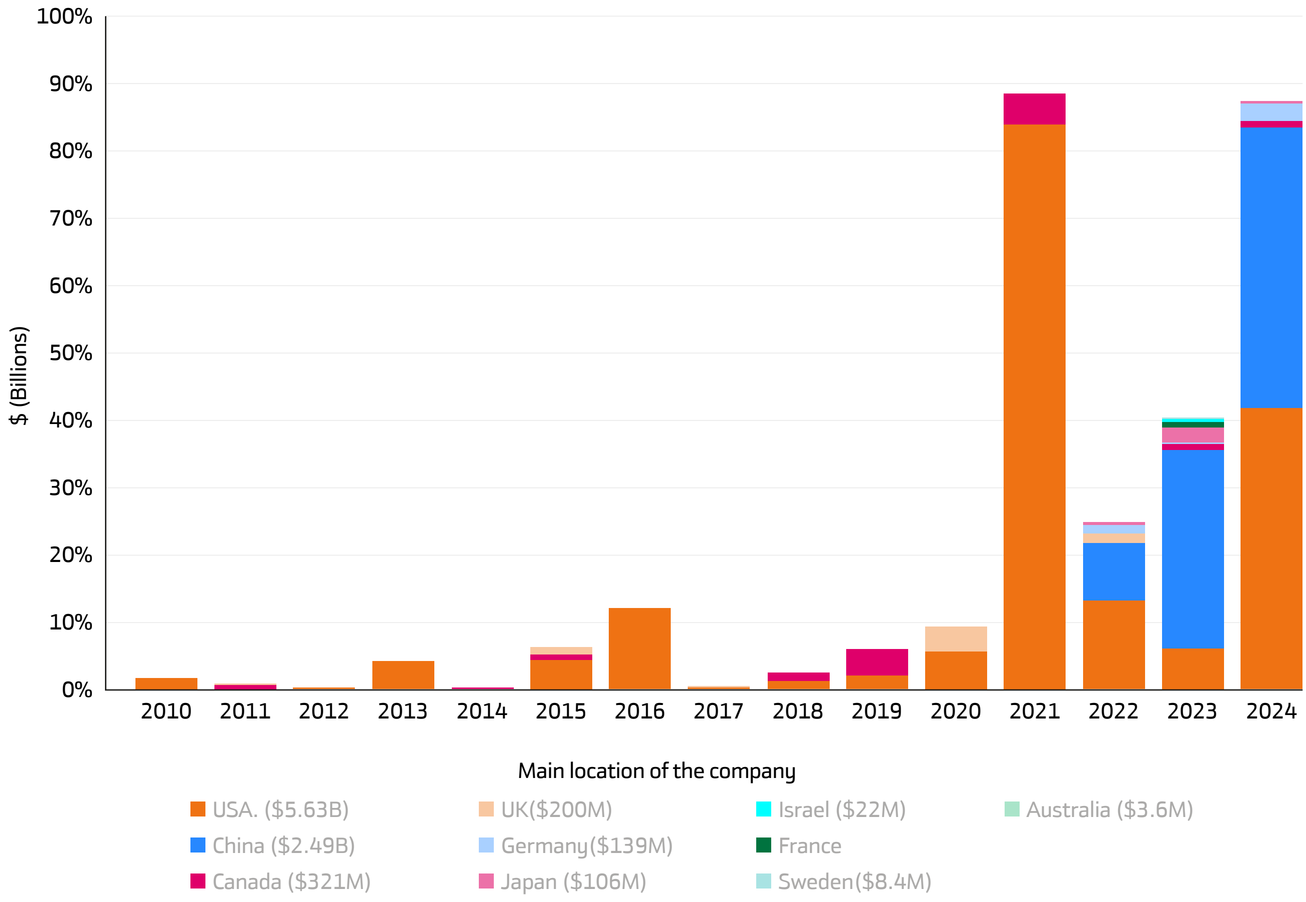
Against this backdrop, many experts argue that **fusion technology roadmaps should integrate measurable milestones, verifiable technical results, and external review mechanisms from the outset** -as already seen in public milestone-based funding programs. This alignment is essential to synchronize the **logic of science with the rules of capital.**

The Investor Ecosystem and Fusion Startups

The dynamism of the fusion industry is reflected in the diversity and ambition of its startups -many of them backed by top-tier international investors. These companies represent different technological approaches (spherical tokamaks, optimized stellarators, inertial fusion) as well as capital-raising strategies tailored to their varying stages of maturity.

Equity Investments in Fusion Companies by Country (partial year)

(Part-year)



Source: https://www.fusionenergybase.com/articles/the-global-fusion-race-is-on

Tokamak Energy (UK)
Raised more than **$250 million**, backed by Legal & General Capital and other institutional funds. Its focus is on spherical tokamaks with high-temperature superconducting magnets.

Xcimer Energy (US)
Secured over **$100 million**, with Breakthrough Energy Ventures as lead investor.

Gauss Fusion (Germany)
Raised **€8 million** in pre-seed funding (2023) and an additional **€9 million** in 2024 through the German Federal Ministry of Education and Research (BMBF).

Renaissance Fusion (France)
After a **€15.5 million** seed round (2022) and a **€10 million** grant from BPI France, it closed a **€32 million** Series A in 2025, led by Crédit Mutuel Impact and Lowercarbon Capital, bringing total funding to over **€60 million**.

Kyoto Fusioneering (Japan/US)
Raised more than **¥13.7 billion** (**around $90 million**), with backing from Marubeni, Nichicon, and In-Q-Tel (the US intelligence-linked strategic investment vehicle).

Proxima Fusion (Germany)
Completed a **€130 million** Series A in June 2025, co-led by Cherry Ventures and Balderton Capital. Total funding now exceeds €185 million, following earlier rounds with Plural Platform and UVC Partners.

Commonwealth Fusion Systems – CFS (US):
Has raised over **$2 billion**, with investors including Breakthrough Energy, Tiger Global, Temasek, and Google. In June 2025, Google signed a strategic agreement to purchase 200 MW of electricity from its future ARC plant in Virginia. In August 2025, CFS closed a **$863 million** Series B2 round, bringing its total funding to nearly **$3 billion**.

Helion Energy (US)
Closed a **$425 million Series F in 2025,** with participation from **Lightspeed, SoftBank Vision Fund 2, and Sam Altman**. Total funding now exceeds **$1 billion.** Its **Polaris prototype** aims to be the first to generate electricity directly from fusion.

According to an analysis by the F4E Fusion Observatory, cumulative investment rose from just over €1.5 billion in 2020 to approximately **€9.9 billion by June 2025**. The regional breakdown highlights the leadership of the United States (61%), followed by China (24%) and Europe (5%), with Germany (€460 million) and the United Kingdom (€417 million) standing out as the main recipients of capital.

Complementing this wave of private capital, governments -particularly the **US Department of Energy**- are rolling out **milestone-based funding mechanisms** that provide early validation signals and strengthen investor confidence.

- China allocates around **$1.5 billion annually in state funding**, according to the same report.
- Europe is moving forward, albeit at a smaller scale. A sign of its vitality: Germany's Marvel Fusion raised €113 million in a Series B round, backed by EQT, **Siemens Energy, and the European Innovation Council**.

Taken together, these figures point to a fusion market attracting more than $8 billion in private capital worldwide, with at least 43 startups actively competing for market leadership. This rapid acceleration -driven by state support, breakthrough technologies, and climate urgency- is redefining fusion: from a distant aspiration to a competitive, investment-ready sector.

$8 billion

billion in private capital worldwide

43 startups

actively competing for market leadership

This landscape illustrates the growing sophistication of the ecosystem, where venture capital (VC) coexists with corporate venture capital (CVC) initiatives and public co-funding programs. The geographic diversity -with key players in Europe, Asia, and North America- signals an increasingly competitive global race. In this context, fostering strong connections between talent, financing, and technological capabilities will be decisive in accelerating the path toward commercial fusion.l.

05

TOWARD A REGULATORY FRAMEWORK FOR FUSION

Toward a Regulatory Framework for Fusion

Fusion is not fission. This principle -emphasized by every expert at the forum- must be at the core of any regulatory framework. The differences are profound: fusion does not produce chain reactions, does not generate long-lived waste, and carries significantly lower radiological risks. Ignoring these distinctions leads to the mistake of applying legacy models that may slow innovation without delivering meaningful safety benefits.

A Strategic Tool, Not a Technical Obstacle

Regulation should be seen as a **strategic enabler** for building a new industry -not as a brake on progress. The process is inherently **social, political, and technical,** which means it cannot be designed in isolation, nor reduced to applying legacy models from other technologies such as fission or particle accelerators. As Patrick White, Head of Fusion Safety and Regulation at the Clean Air Task Force (CATF), emphasizes: a well-designed regulatory framework is **essential for the success of fusion energy**.

From his role at **CATF**, White leads an international working group aimed at building **global regulatory consensus** -enabling fusion deployment without compromising safety. His approach is grounded in **three core principles:**

- **Risk-proportional regulation**
  There is a fundamental difference between a laboratory facility handling micrograms of tritium and a DEMO-scale plant requiring several kilograms.

- **Performance-based oversight**
  Safety should be measured by outcomes, not by rigid, predefined technical prescriptions.

- **Technology inclusivity**
  The framework must apply across all fusion approaches, without favoring specific designs.

Patrick White

Watch video

White warns against two pitfalls: over-regulating fusion as if it were fission, and conversely, under-regulating by applying particle accelerator rules to contexts with far higher radiological exposure.

“The key is to scale regulation intelligently -tailored to both the technology and the moment,” he stresses.

The Value of Certainty: An Industry Perspective

Experts converged on a critical point: regulatory certainty is essential to mobilize investment, reduce risk, and accelerate time-to-market.

Susana Reyes (Xcimer Energy) underscores the importance of frameworks such as **U.S.** 10 CFR Part 30, which allow requirements to be adapted to specific technologies. At Xcimer, regulatory logic is embedded from the design stage -minimizing occupational doses and accident risks- while collaborating with institutions such as UNED, Savannah River, and the UK's LIBRTI program to validate solutions in breeding and high-energy neutrons.

Susana Reyes

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Lucio Milanese (Proxima Fusion) emphasizes the need to strike a balance between rigor and agility. Drawing on his experience, he points out that in some ITER projects, as much as **70% of the cost of certain components is driven by regulatory requirements rather than technical value**: "We're paying more for the paperwork than for the metal." He advocates for **graduated frameworks** that evolve alongside the sector -avoiding disproportionate burdens in early stages while anticipating the demands of commercial deployment.

Lucio Milanese

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Richard Pearson

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Expanding the perspective, **Richard Pearson** (then representing Kyoto Fusioneering) stresses that **good regulation is also good communication**. The UK example, where the Energy Act 2023 excludes fusion from the conventional nuclear regime, demonstrates a **flexible pathway under civilian oversight.**

A Global Vision: Harmonization and Shared Learning

Building a global regulatory framework for fusion -inspired by models from civil aviation- could accelerate industry development and enable the exchange of best practices. At the same time, many components of magnetic fusion -such as superconducting magnets, cryogenics, and vacuum systems- are also used in particle accelerators and could benefit from shared regulatory standards.

This is the case made by Ralf Kaiser, Program Director at the International Centre for Theoretical Physics (ICTP), who stresses the need for harmonization and mutual learning.

His seven recommendations outline a pragmatic roadmap:

- Mutual recognition of licenses among producing countries.
- Multilateral agreements allowing countries without regulatory capacity to adopt external frameworks.
- Creation of an international body specifically dedicated to fusion regulation.
- Safeguards against misuse of fusion machines for non-peaceful applications.
- Global-scale training programs for technical and regulatory expertise.
- Public outreach initiatives to improve societal perception.
- Principle-level harmonization without undermining national sovereignty.

As Kaiser puts it: “Regulation should not hold back innovation -it should guarantee its acceptance and scalability worldwide.”

Ralf Kaiser

Watch video

From Exception to Norm: Building a New Regulatory Culture

The forum reached a clear consensus: **it is not enough to adapt existing rules**. Fusion requires its own regulatory architecture -one that reflects its technological specificity, real risk profile, and industrial ambition. To achieve this, three action lines were proposed:

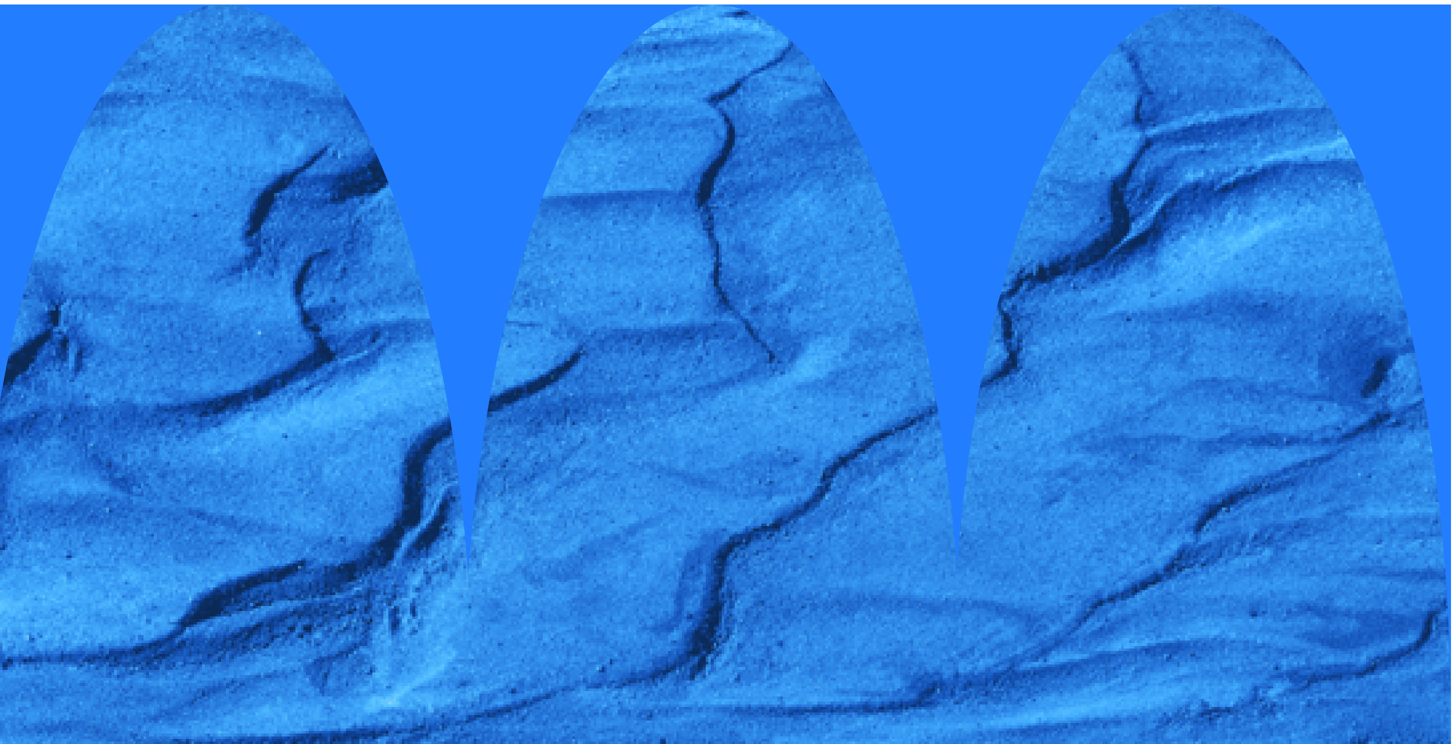
Progressive design Scalable frameworks that evolve from laboratory setups to full industrial plants.

Early collaboration Regulation as a co-design process between industry, government, and society.

Global vision toward harmonized principles that provide certainty and lower barriers for multinational projects.

Fusion regulation is not just a compliance issue -it is a **strategic factor for commercial deployment**. As **Patrick White** reminds us: “We cannot apply yesterday’s rules to tomorrow’s technologies.”

In short, smart, proportional, and collaborative regulation will be one of the keys to moving fusion from promise to reality.



06

PEOPLE AND SKILLS TO DRIVE FUSION FORWARD

People and Skills to Drive Fusion Forward

Without people, there is no industry. Every expert at the forum agreed: the success of fusion depends not only on scientific breakthroughs or financial capital, but also on the ability to train, attract, and retain the talent required to build, operate, and scale this new global energy infrastructure.

The challenge is immense. This is not about converting an existing sector -it is about creating from scratch a cross-cutting, highly specialized, and globally distributed industry. And time is not on our side.

A Structural Bottleneck

Talent development is now one of the **biggest bottlenecks** for fusion's progress. Steven Biegalski, Head of the Nuclear and Radiological Engineering and Medical Physics Program at Georgia Tech, puts it bluntly: while private investment is surging, specialized educational programs are not keeping pace. "We are not training enough people to run this industry. And the programs that do exist lack the scale and the funding required," he warns

The challenge is one of **both scale and focus**. Most current programs are designed for research, not for industrialization. The traditional model -centered on plasma physics or materials science- is no longer enough. This is the moment for engineers.

Until now, fusion has been an almost exclusively physics-driven field, but scaling to commercial deployment requires professionals who can design, integrate, and build complete systems.

Commercial fusion demands a **new kind of professional profile**: hybrid, interdisciplinary, and skilled in areas such as systems engineering, regulation, sustainability, power electronics, cryogenics, artificial intelligence, and advanced manufacturing. As **Biegalski** stresses:

"The transition to commercial scale requires skills that today's universities are simply not training for."

Ralf Kaiser (ICTP) reinforces this concern with hard numbers: today, there are only **2,000 to 5,000 plasma physicists worldwide**. Roughly **40% of those working in fusion projects hold or are pursuing a PhD**. But a global energy industry -capable of producing electricity, hydrogen, industrial heat, and advanced materials- will need **hundreds of thousands of specialized professionals within the next two decades**. That means not just scientists, but also **engineers, technicians, operators, regulatory specialists, sustainability experts, and advanced manufacturing professionals.**

Both experts agree: it is not just about expanding educational supply. It requires building a **new training infrastructure** with **international partnerships**, **flexible models, accredited centers for hands-on practice, and enough qualified faculty. Biegalski** warns that many university departments lack the capacity to create specialized courses, and there are not enough accredited technical centers to fill the gap.

He insists that education must be embedded in the industrial strategy for fusion from the very beginning -not as an afterthought, but as a core enabler.

Ralf Kaiser

Watch video

Steven Biegalski

Watch video

In this context, networks such as ENEN (European Nuclear Education Network) are working to strengthen nuclear and fusion capacity-building from a pan-European perspective. **Georgia Tech** is one of the few US institutions integrated into this ecosystem, actively participating in the ENEN2+ project, which aims to standardize programs and facilitate talent mobility.

Kaiser also warns of a troubling disconnect: much of today's talent is concentrated in public research centers, while the industry's future growth will be driven by the **private sector**, which is competing for professionals in an increasingly demanding and global labor market. This raises a pressing challenge around **attracting and retaining qualified talent**, particularly in regions with lower densities of scientific institutions.

> The fusion revolution will also be an educational revolution -both qualitative and quantitative. More people must be trained, and they must be trained differently, faster, and at greater scale.

Innovating in Education

Steven Biegalski argues for a **dedicated educational roadmap for fusion**, built on three pillars: **stable funding, international collaboration, and workforce retraining from adjacent sectors**. The idea is to rethink the **entire training model** with an industrial, scalable, and global logic.

Ralf Kaiser reinforces this vision with the example of the **ICTP**, which already trains **10% of all medical physicists in developing countries** through joint programs with hospitals, universities, and international agencies. This **hybrid model** -academic training combined with hands-on practice- could be applied to fusion: **technical training, industrial rotations, international licensing, and continuous professional development**.

Kaiser also suggests looking to the aerospace sector as a reference for capacity-building. In the future, not every country will be a technological leader in fusion, but each could play a role within the global ecosystem. **Sehila González** (Clean Air Task Force) distinguishes three types of countries:

- **Users**
  With regulatory frameworks, basic technical knowledge, and the ability to operate facilities in partnership with fusion companies.
- **Contributors**
  Adding industrial capacity, enabling technologies, and local workforce development.
- **Developers**
  Leading national technology programs able to design, build, and operate prototype fusion devices..

This model calls for tailored educational pathways for each role: from plant operators and maintenance technicians to frontier scientists and regulatory program managers. And that requires innovation not only in what is taught, but also in how, where, and with whom talent is trained.

Investing in People, Not Just Projects and Startups

Wilfried Vanhonacker, trustee of the Foundation, offered a fundamental reflection: "If we believe fusion is going to change the world, we cannot keep training professionals as if nothing were going to change." **Vanhonacker** argues that just as we invest in **infrastructure and startup**s, both public and private capital must also invest in **talent**. "We need an investment mindset that values human capital, not just physical capital," he stresses. He proposes the creation of a "Fusion Business School" -an academic and professional environment that integrates **industrial vision, technical expertise, executive training, and innovation.**

Artificial intelligence is also emerging as a **key lever**. Juan Zufiría, President of the Foundation, calls for training **hybrid profiles** -professionals fluent in both **fusion physics** and artificial intelligence. This convergence, he argues, can multiply talent productivity and accelerate sector development. Steven Biegalski (Georgia Tech) confirms the trend: many of his students are already using AI to analyze large datasets from devices such as DIII-D, applying it as a **complement to traditional physics expertise**. "It's a 'with,' not an 'or'," he summarizes.

Ralf Kaiser (ICTP) adds an important nuance: while AI can accelerate processes and expand capabilities, it cannot replace classical engineering or expertise in critical technologies such as cryogenics, materials, or vacuum systems. What it can do is **free up resources, shorten experimental timelines, and open new avenues for scientific collaboration**.

The consensus is clear: without talent, there will be no industry. And building that talent will require investment, planning, and new educational structures tailored to the unique challenges of fusion.

Reskilling, Ecosystems, and Lifelong Learning

As we have seen, the transition to a commercial fusion industry cannot afford to wait decades for a completely new generation to be trained from scratch. An immediate path forward is the reskilling of professionals from adjacent sectors such as aerospace, nuclear, semiconductors, and advanced manufacturing. Many of the knowledge bases, methodologies, and competencies already present in these industries can be directly applied to fusion, provided that reskilling programs are tailored to the sector's specific challenges.

Spain already has meaningful assets in this effort. Institutions such as CIEMAT and the University of Seville bring decades of experience in fusion technologies, advanced materials, and specialized technical training. Initiatives like FUSION EP at CIEMAT are training engineers in magnetic fusion on a pan-European scale, while the Fusion2Grid project at the University of Seville uses real technology platforms to prepare professionals with hands-on experience.

In addition, master's and postgraduate programs across Spanish universities could be scaled up and adapted more rapidly if coordinated under a national roadmap.

But isolated programs or one-off reskilling efforts will not be enough. The pace of technological change demands a culture of continuous upskilling and reskilling.

Competencies must evolve in step with innovation, through agile, collaborative models rooted in the real needs of the fusion industry.

07
CONCLUSIONS AND RECOMMENDATIONS

Conclusions and Recommendations

As this report has shown, fusion energy is no longer a distant horizon -it is an emerging industry attracting unprecedented levels of capital, talent, and scientific breakthroughs. Turning this promise into reality requires more than technological innovation. After engaging with leading experts at the Future Trends Forum (FTF), the Bankinter Innovation Foundation has identified a pivotal moment: the window of opportunity is now.

Fusion is not only a response to the climate crisis and the imperative of decarbonizing the energy system; it is also a strategic lever for global competitiveness, energy security, and the creation of new industries that can transform the economy. Its benefits extend far beyond power generation -into advanced materials, applied AI, remote robotics, and additive manufacturing- but only if we accelerate the transition from laboratories and experimental facilities to full-scale industrial deployment.

Based on the insights of the think tank experts, the Foundation recommends coordinated action across five urgent strategic priorities:

Technology	Accelerate the leap from development to real-world application by deploying critical test infrastructures, solving subsystem integration challenges, and leveraging external enabling technologies.
Investment and Public–Private Collaboration	Mobilize capital and forge strategic partnerships to connect fusion to the grid and deliver reliable electricity.
Talent	Design and execute a global strategy to train, retrain, and attract the technical and leadership talent needed to scale the sector.
Regulation	Develop agile, safe, and globally aligned regulatory frameworks tailored to the real risks of fusion -not the legacy of fission.
Communication	Build a compelling and credible narrative that generates public trust, legitimacy, and societal license to operate.

What is at stake goes far beyond a new energy source. If we fail to move at the right pace, we risk forfeiting **a historic opportunity for technological, industrial, and societal leadership**. Fusion has the potential to redefine the global energy future, and Europe must position itself at the forefront. The path is clear: commit to ambitious projects, strengthen international collaboration, and mobilize all available resources to ensure fusion arrives in time.

Pillar 01

Technology: From the Lab to the Real World

The technological challenge for fusion is clear: the next step must be a decisive leap from laboratory experiments to fully integrated experimental devices that can test how systems perform and operate under real-world conditions.

These projects are essential to accelerate the path toward building a robust and competitive fusion industry.

Recommendations

Advance experimental fusion devices

To validate designs, processes, and systems under realistic operating conditions, tackling integration challenges head-on.

Accelerate progress on critical components

From deploying test infrastructures to developing advanced materials and coolants. ITER should be leveraged as both a global learning platform and a testbed for components.

Build the supply chain early

Identifying future component needs and fostering partnerships with industry to secure large-scale production capacity.

Leverage external technologies and cross-industry expertise

From aerospace to fission nuclear power- to integrate complex systems more efficiently.

Expand spillover opportunities

By clarifying how fusion-related technologies -advanced materials, remote robotics, radiation-hardened electronics, cryogenics- can be applied across other industries, creating channels for investment, industrial partnerships, and sustained political support.

Pillar 02

Investment and Public-Private Partnerships

Getting fusion power onto the grid as soon as possible will require mobilizing capital at scale and building strategic alliances between the public and private sectors.

Fragmented project funding won't be enough; what's needed is an ambitious, coordinated approach that accelerates the construction of experimental fusion devices while de-risking investment.

Recommendations

Position the public sector as a strategic partner

Not just a funder, actively shaping objectives and tracking progress.

Launch pilot public–private partnership (PPP) programs

focused on building fully integrated experimental fusion devices, even if subsystems are at different stages of maturity. This approach will validate designs and speed up grid connection.

Include clear monitoring mechanisms and verifiable success metrics (certifications, mobilized investment, customer validation).

Adopt competitive, milestone-based funding models

Adopt competitive, milestone-based funding models -similar to NASA's- through European calls that support multiple prototype fusion projects.

Simplify and harmonize frameworks

For intellectual property and infrastructure access, removing barriers that slow collaboration and discourage new industrial players..

Develop regional fusion innovation hubs

Where companies, startups, research centers, and industrial capabilities converge to scale the technology.

This approach would allow Europe to position itself as a global leader in a market with extraordinary potential returns. Those who lead partnerships today will attract the best talent, set the rules of the game, and secure the industrial base that will make reliable fusion power a reality in the next decade.

Pillar 03

Talent: Building the Workforce of the Future

Developing fusion energy will demand a deliberate, forward-looking talent strategy.

Given the pace of technological progress, action is needed now to ensure the right expertise is in place at every stage of development.

A central challenge is the reskilling of technical professionals from adjacent industries -aerospace, nuclear, automotive, energy, and others. These professionals already bring a strong engineering foundation and can adapt quickly to the unique demands of the fusion sector.

Recommendations

Establish a global educational roadmap

Establish a global educational roadmap for fusion, coordinated internationally, that anticipates the technical, scientific, and leadership profiles needed in the short, medium, and long term..

Launch targeted reskilling programs

To attract talent from adjacent industries. These programs should be flexible, fast to implement, and designed in active partnership with industry.

Promote alliances between universities, technology centers, and companies

with joint programs that combine academic training, hands-on internships in startups and established firms, scholarships, and international certifications.

Facilitate international mobility

Creating networks that allow students and professionals to train at leading centers across countries. These initiatives should go beyond current programs and adapt to the specific needs of fusion.

Investing in talent is a long-term competitive advantage. Countries and organizations that lead in fusion education will become hubs of excellence, capable of attracting investment, industry, and global partnerships.

Just as importantly, positioning fusion as an educational, innovative, and technological driver strengthens its narrative as a sector with direct and positive societal impact.

Pillar 04

Regulation: Designing a Global, Agile, and Safe Framework

Regulation will be a critical enabler -or barrier- for the deployment of fusion energy. While its radiological risks are fundamentally different from those of fission, many countries still apply legacy frameworks that slow down progress.

Divergent approaches across jurisdictions add unnecessary costs, legal uncertainty, and obstacles to building a global market.

Recommendations

Develop a global reference framework for licensing and certification

Drawing on models from civil aviation, where the U.S. and Europe mutually recognize technical licenses. Such agreements could accelerate grid connection for fusion plants and open access to technology for developing countries.

Adopt risk-based, adaptive regulation

Adopt risk-based, adaptive regulation that sets clear safety objectives while allowing operators flexibility in how they achieve them -avoiding rigid, prescriptive rules that stifle innovation.

Avoid regulatory lock-in from fission

By training new experts and building regulatory capacity specifically tailored to fusion.

Introduce regulatory incentives that enable safe progress

Such as sandboxes for experimentation, fast-track procedures for low-risk technologies, and flexible frameworks for demonstrators.

Establish a global institutional leader for fusion regulation

A body that can coordinate licensing, safeguards, capacity-building, and public engagement -similar to how IRENA (the International Renewable Energy Agency) operates for renewables.

An agile, transparent, and harmonized regulatory framework would accelerate the arrival of fusion, build public trust, attract investment, and enable global adoption. The time to act is now -before regulatory barriers become structural bottlenecks.

Pillar 05

Communication: Building Narrative, Trust, and Social License

For most of society, fusion remains largely unknown. Despite record levels of investment and major scientific progress, its public narrative is weak, fragmented, and disconnected from citizens' concerns. Confusion with fission, fears around tritium, and doubts about feasibility continue to feed skepticism.

This lack of a compelling story carries real costs: without public trust, there will be no social legitimacy and no sustained path to industrial deployment. And trust is not inherited -it must be earned through education, transparency, and dialogue, starting now.

Society needs to know that fusion exists, that it is within reach, and that it has the potential to transform the global energy system, strengthen Europe's energy independence, and rebalance the geopolitical landscape.

A clear and ambitious narrative can position fusion as a cornerstone of the energy transition: a technology that can complement -and ultimately surpass- the role of today's renewables.

Recomendaciones

Develop a shared narrative

Beyond the technical details, fusion needs a story -how it reshapes the energy model, addresses climate change, and creates industrial opportunities, jobs, and technological leadership.

Invest in public education today

Do not wait for the first plant to go live. Communicate proactively, with clear and accessible messages, emphasizing the difference from fission and the safety-by-design logic of fusion.

Engage social and educational stakeholders

Schools, universities, journalists, opinion leaders, and even cultural institutions. Social license is not won with a press release -it is built in every public conversation.

Manage expectations with honesty

Avoid triumphalism. Credibility comes from explaining both the extraordinary progress and the challenges still ahead.

Fusion will also be won in the hearts and minds of people. A strong narrative can accelerate institutional change, attract talent, mobilize investment, and create the network effects needed for scale.

A Historic Moment for Spain and for Europe

Europe did not lead the digital revolution. Nor does it dominate today's race in artificial intelligence. But in the race for fusion energy, there are still no winners. This is open ground -where knowledge, scientific collaboration, and industrial vision can make all the difference.

Here, Europe -and Spain in particular- holds significant advantages: a world-class research base, flagship public projects such as IFMIF-DONES, ITER, and DEMO, and an emerging ecosystem of companies with global ambitions. But these advantages are neither structural nor guaranteed. They are windows of opportunity -and they can close quickly if not translated into decisive action.

The question is immediate and unavoidable: do we want to be just a market -or a driver? Buyers of someone else's technology -or builders of a strategic, exportable industry of our own?

Fusion is TODAY a monumental energy promise. And it is a bet on sovereignty, innovation, and industrial leadership -for Europe, and for Spain.

08
GLOSSARY

Glossary

Apantallamiento neutrónico
Conjunto de materiales o estructuras diseñadas para **proteger los componentes del dispositivo de fusión** (especialmente los imanes y sistemas electrónicos) del bombardeo de neutrones de alta energía producidos por la fusión. El apantallamiento reduce el daño en los materiales y ayuda a mantener la seguridad y la longevidad de la instalación.

Breeding
The process by which a fusion device generates the tritium fuel it needs. Materials such as lithium are placed around the fusion zone; when neutrons from the reaction collide with lithium, they transform it into tritium.

Breeding blanket
A structure surrounding the plasma in a fusion device. It contains lithium (in liquid or ceramic form) to breed tritium, while also absorbing the heat carried by neutrons and transferring it to the power conversion system.

Cryogenics
The set of techniques used to reach and maintain extremely low temperatures (below −150 °C). In fusion, cryogenics is essential for cooling superconducting magnets and, in some cases, solid deuterium–tritium fuel.

Deuterium
A stable isotope of hydrogen (H-2) with one proton and one neutron. Found abundantly in seawater, it is one of the basic fuels for fusion, together with tritium.

Detritiation
The process of removing or recovering residual tritium from gases, liquids, or materials inside a fusion device. It is vital for minimizing tritium losses, reducing radiological risks, and recycling this scarce fuel within the system.

Divertor
The part of a fusion device responsible for extracting extreme heat and plasma impurities. It is one of the most demanding engineering components, as it must withstand very high thermal and particle loads.

Firm power
Electricity that can be delivered consistently and predictably, regardless of external conditions such as weather. Fusion aims to provide firm power.

Field-Reversed Configuration (FRC)
A type of magnetic confinement device where the plasma takes on a compact cylindrical shape, and the plasma's own magnetic field reverses the direction of the external field. FRCs are smaller and simpler than tokamaks or stellarators and may be suitable for advanced fuels such as deuterium–helium-3.

Fuel capsule or target
A tiny sphere containing fusion fuel (typically deuterium and tritium). In inertial confinement systems, the capsule is compressed by lasers or particle beams until the fuel inside reaches fusion conditions.

Gain (Q factor)
The ratio of energy obtained from fusion to the energy input into the fuel.

$Q = 1$: the reaction produces exactly as much energy as is injected.

$Q > 1$: the reaction produces more energy than it consumes.

Helium
The main byproduct of deuterium–tritium fusion. It is a noble, inert, and non-radioactive gas.

High-temperature superconductors (HTS)
Materials that conduct electricity with zero resistance at much higher temperatures than conventional superconductors.

Traditional superconductors operate near absolute zero (−269 °C, using liquid helium).

HTS operate below about −135 °C, allowing the use of cheaper liquid nitrogen cooling.

In fusion, HTS enable stronger, more compact, and more efficient magnets, critical for next-generation tokamaks.

Inertial confinement
A fusion technique that uses lasers or particle beams to rapidly and intensely compress a tiny fuel capsule, causing the nuclei to fuse before the capsule disintegrates.

Laser (in fusion)
A device that emits a concentrated, high-power beam of light. In inertial confinement, multiple lasers are aimed at a fuel capsule to compress it until the fuel reaches fusion conditions.

Liquid wall (FLiBe)
A system in which the inner walls of a fusion device are lined with molten salts of fluorine, lithium, and beryllium (FLiBe). The liquid wall absorbs heat and neutrons, breeds tritium, and protects solid structures from intense particle bombardment.

Magnetic confinement
A method of keeping plasma hot and stable by using strong magnetic fields to prevent it from touching the walls of the fusion device. Tokamaks and stellarators are based on this principle.

Magnetized Target Fusion (MTF)
A hybrid approach combining features of magnetic and inertial confinement. A magnetically confined plasma is rapidly compressed by a mechanical or explosive liner to reach fusion conditions. MTF offers the potential for smaller, less costly fusion devices.

MJ (megajoule)
A unit of energy equal to one million joules. To visualize: 1 MJ is roughly the energy needed to boil three liters of water.

MW (megawatt)
A unit of power equal to one million watts (1 J/s). Used to describe how much energy a system can generate or consume per unit of time.

Net energy
The difference between the energy produced by fusion and the total energy required to sustain the process and run all supporting systems. Achieving positive net energy is essential for commercial viability.

Neutron
An electrically neutral particle found in atomic nuclei. In fusion, neutrons carry most of the released energy and are used to breed tritium and generate heat.

Neutron-resistant materials
Advanced alloys and coatings capable of withstanding the intense neutron bombardment inside a fusion device, preventing rapid material degradation.

Neutron shielding
A set of materials or structures designed to protect fusion device components -especially magnets and electronic systems- from the intense bombardment of high-energy neutrons produced during fusion. Shielding reduces material degradation and helps ensure both safety and the long-term reliability of the facility.

Plasma
The fourth state of matter, formed when a gas is heated so much that its electrons separate from the nuclei, leaving charged particles (ions and electrons) that move freely. In fusion devices, plasma can exceed 100 million °C.

Scientific ignition
Achieved when the energy released within the fuel equals the energy delivered directly into it. Expressed as $Q = 1$, this definition excludes the total energy consumed by external systems such as lasers or magnets.

Spillover technologies
Technologies developed for fusion that find applications in other industries. Examples include superconductors adapted for power grids, radiation-resistant materials for aerospace, and robotics designed for extreme environments.

Stellarator
A type of magnetic confinement device, shaped like a twisted torus. Unlike tokamaks, stellarators rely entirely on external magnets, allowing continuous operation without induced plasma currents.

Technology Readiness Levels (TRLs)
A scale measuring the maturity of a technology, from TRL 1–3 (basic research and proof of concept), to TRL 4–6 (prototype validation and demonstration in relevant environments), to TRL 7–9 (fully integrated systems ready for commercial deployment). Many fusion subsystems remain at intermediate TRLs.

Tokamak
The most mature type of magnetic confinement device, shaped like a torus. Tokamaks use powerful magnetic fields to keep plasma hot and stable long enough for fusion to occur.

Tritium
An isotope of hydrogen (H-3) with one proton and two neutrons. It is one of fusion's key fuels, along with deuterium. Because it is scarce in nature, tritium must be bred inside fusion devices.

Tritium Breeding Ratio (TBR)
The ratio of tritium produced to tritium consumed in a fusion device.
TBR = 1: production equals consumption.

TBR > 1: production exceeds consumption, a prerequisite for self-sufficiency.

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