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Fusion Energy: From Scientific Promise to Technological

Future Trends Forum Report Preview – #FusionForward 2025

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This document is a summary of the main messages and discussions from the international forum "Fusion Forward," held on June 4–5 in Madrid. Throughout the fall of 2025, Fundación Innovación Bankinter will publish a full report including detailed conclusions and specific recommendations to accelerate the development and deployment of fusion energy. This translation was generated using Artificial Intelligence and may contain errors.

Fusion Takes the Stage

For decades, fusion energy has been the great unicorn of the energy transition—a clean, safe, and inexhaustible power source that always seemed to be 30 years away. Today, for the first time, that horizon is beginning to take shape with concrete timelines, massive investments, and real prototypes. **Fusion is no longer just a scientific challenge; it has become a technological, industrial, and geopolitical one.**

This shift comes at a critical moment: the growing urgency to decarbonize the economy in response to the accelerating climate crisis has coincided with rising global energy demand—driven by massive digitalization, the expansion of artificial intelligence, and the electrification of transport. This mix of environmental, technological, and economic pressures has pushed fusion to the center of a new strategic conversation about the future of energy.

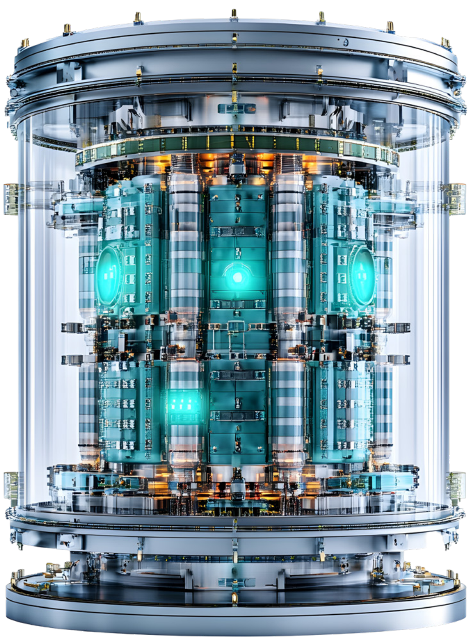
At the same time, the innovation ecosystem has evolved. In contrast to the traditional model of large-scale public research projects, the past decade has seen the emergence of more than 40 highly specialized fusion startups, many backed by venture capital and climate impact funds.

Companies like Commonwealth Fusion Systems, TAE Technologies, Tokamak Energy, Gauss Fusion, Renaissance Fusion, Kyoto Fusioneering, Xcimer Energy Corporation, and Proxima Fusion have raised billions of dollars.

This wave of private investment is reshaping the pace, expectations, and—above all—the culture of the fusion sector.

Against this backdrop, the Future Trends Forum of Fundación Innovación Bankinter brought together in Madrid a group of thirty top-tier international experts—scientists, investors, technologists, business leaders, and public policy makers—to reflect on the strategic role of fusion and the path toward its industrial viability.

The goal: to identify, from a global and cross-sector perspective, the key conditions that must align for this technology to make the leap to industrial reality—and to explore the role that Spain and Europe can play in that future.



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What is fusion energy?

Fusion is the reaction that powers the Sun. Reproducing it on Earth—in a controlled and cost-effective way—could revolutionize the global energy system. **Physically speaking, fusion is the process by which two light atomic nuclei, such as those of hydrogen, combine to form a heavier nucleus, releasing a large amount of energy.**

Unlike fission, which splits heavy nuclei and generates long-lived radioactive waste, fusion produces a much cleaner and safer form of energy. While it does produce some radioactive byproducts, they are less intense and have much shorter half-lives. Fusion also does not require fissile materials capable of triggering chain reactions, emits no greenhouse gases during operation, and carries no risk of catastrophic nuclear accidents.

To release energy through fusion, the fuel must be heated to extreme temperatures (over 100 million degrees Celsius), transforming it into plasma, the fourth state of matter.

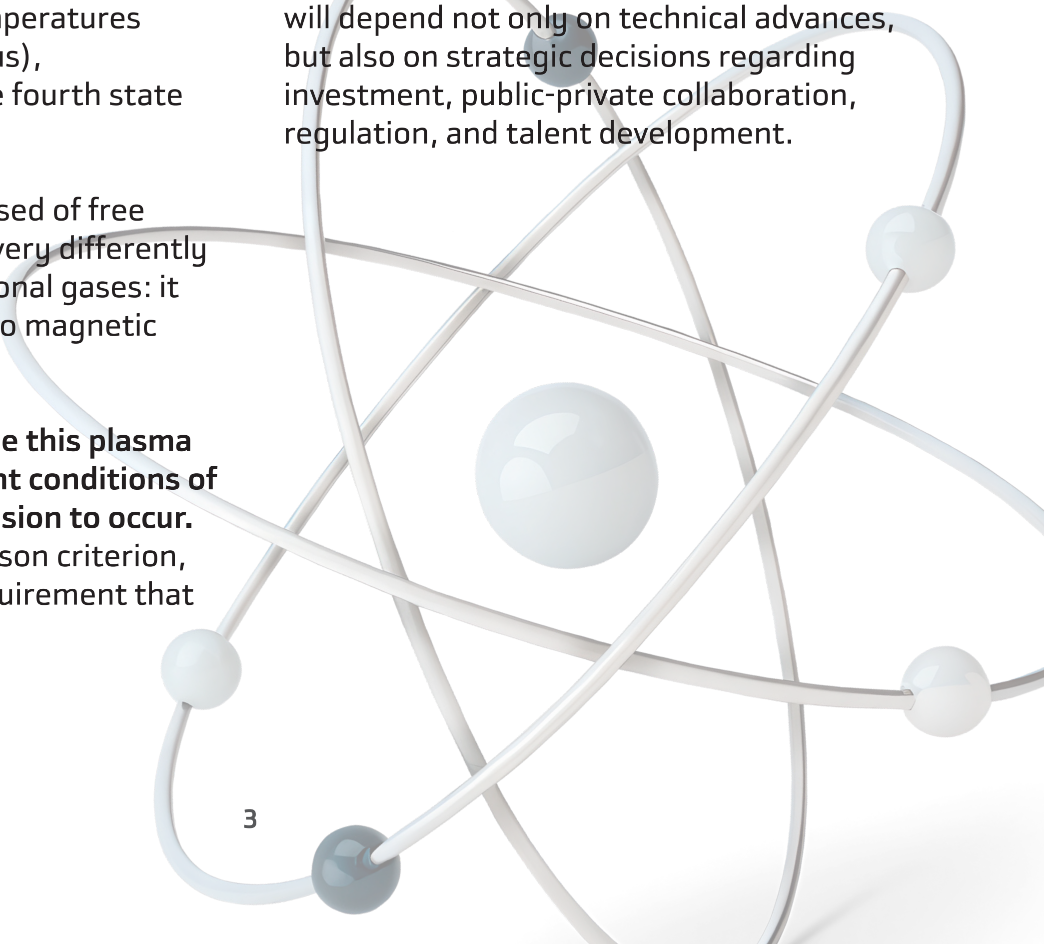
Plasma is an ionized gas composed of free nuclei and electrons, behaving very differently from solids, liquids, or conventional gases: it conducts electricity, responds to magnetic fields, and is highly unstable.

The main challenge is to confine this plasma long enough and under the right conditions of density and temperature for fusion to occur. This balance, known as the Lawson criterion, is the fundamental physical requirement that underpins all reactor designs.

There are currently two major technological approaches to achieving these extreme conditions: magnetic confinement, which uses intense magnetic fields in devices such as tokamaks and stellarators; and inertial confinement, which employs lasers or particle beams to compress small fuel capsules.

Although neither has yet achieved sustained net energy gain under commercial conditions, recent breakthroughs—such as ignition at the National Ignition Facility (NIF) in the United States or the use of high-temperature superconductors in compact reactors—are accelerating progress and bringing fusion closer to the energy market.

If in the past fusion was "always 30 years away," today it is no longer a scientific promise—it is an innovation and engineering challenge at an industrial scale. Bringing this energy to the power grid—and doing so soon—will depend not only on technical advances, but also on strategic decisions regarding investment, public-private collaboration, regulation, and talent development.



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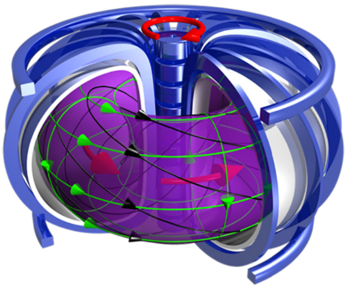
Challenges

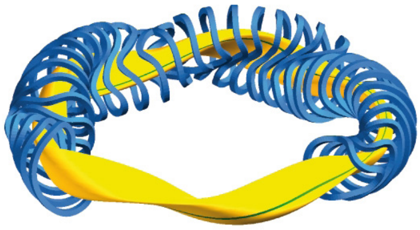
The race toward fusion energy is now a major engineering challenge, where **different technologies are progressing at uneven speeds but converging on a common goal: to generate clean, safe, and abundant energy.** The discussion at the forum made it clear that the question is no longer "if" fusion is possible, but rather "how and when" we will succeed in turning it into a competitive and scalable energy source.

Three Technological Pathways Underway

There are three main technological pathways currently under development:

TOKAMAKS
Devices like the JET reactor or the one under development at ITER use intense magnetic fields in a toroidal geometry to confine the plasma. They have achieved the most significant experimental progress to date, although their complexity and size present major challenges for scalability.





STELLARATORS
Devices like Wendelstein 7-X or the future reactor from Renaissance Fusion feature a more complex but inherently more stable geometry. They allow for continuous operation without the need for pulses, making them attractive for baseload power generation—though their construction

INERTIAL CONFINEMENT
Used at facilities like the National Ignition Facility (NIF) in the U.S., this approach employs lasers to compress deuterium-tritium fuel capsules. In 2022, it achieved ignition for the first time—producing more energy than was absorbed by the fuel—marking a historic milestone.
In April 2025, NIF reached its most significant achievement to date: generating 8.6 megajoules of fusion energy in a single experiment, using 2.08 megajoules of laser energy to initiate the reaction. This means the energy output was more than four times the energy delivered directly to the fuel. This result far surpasses previous records and confirms that inertial confinement ignition, although still experimental and far from the performance needed for a commercial power plant, is advancing rapidly.

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From Physics to Systems

"We are no longer in the era of plasma physics. We are entering the era of fusion technology." With this statement, one of the forum participants summed up a widely shared consensus: the fundamental physics is now well established. The challenge today lies in turning that knowledge into operational systems—through robust engineering, advanced materials, and scalable industrial processes.

The Challenges, According to experts

1. Tritium management and fuel cycle:
One of the world's leading fusion engineering experts noted that many key obstacles lie not within the plasma itself, but in the surrounding systems: how to safely produce, recover, and handle tritium, and how to enable the reactor to regenerate its own fuel using lithium-based blankets, known as breeding blankets. This was identified as one of the least mature—and most critical—areas on the path to commercialization.

2. Materials under neutron exposure:
Experts emphasized the enormous challenges posed by fast neutrons impacting the reactor's internal walls. This will require not only new materials, but also dedicated testing facilities—such as IFMIF-DONES in Spain—that can assess material performance under real fusion conditions.

3. Full system integration and efficiency:
Several experts highlighted the need to view reactors as fully integrated systems. It's not enough to achieve fusion—heat must be captured, converted into electricity, components must be cooled, and all of this must be done efficiently. They also stressed that any viable solution must address safety, maintenance, and operational costs right from the design phase.

A Shift in Mindset

"What we need now is not another incremental advance in plasma, but the integration of all subsystems into a functional device—even if it's not yet perfect." Most experts agreed that the fusion sector must adopt more iterative approaches, similar to those used in technology and business development. This means accepting a degree of technical uncertainty, prioritizing functional demonstrators, and working with minimum viable product (MVP) principles—rather than waiting for every subsystem to be perfected before moving forward.

Enabling Technologies

Fusion energy cannot progress without a set of cross-cutting technologies that must mature and be integrated alongside the reactor itself. During the forum, experts agreed that many of the key components required for commercial operation are still at low levels of technological maturity—but decisive steps are being taken to shorten development timelines.

Widespread Low Technological Maturity

According to several experts at the forum, most of the subsystems required for a commercial reactor—such as the breeding blanket, neutron-resistant materials, remote maintenance systems, advanced magnets, thermal conversion, or the tritium cycle—are still at low levels of technological maturity (TRL < 4). This means that while they are theoretically understood and have undergone experimental testing, they have yet to be validated under relevant operational conditions. **Bridging this gap will require advanced testing facilities and systematic technology integration strategies.**

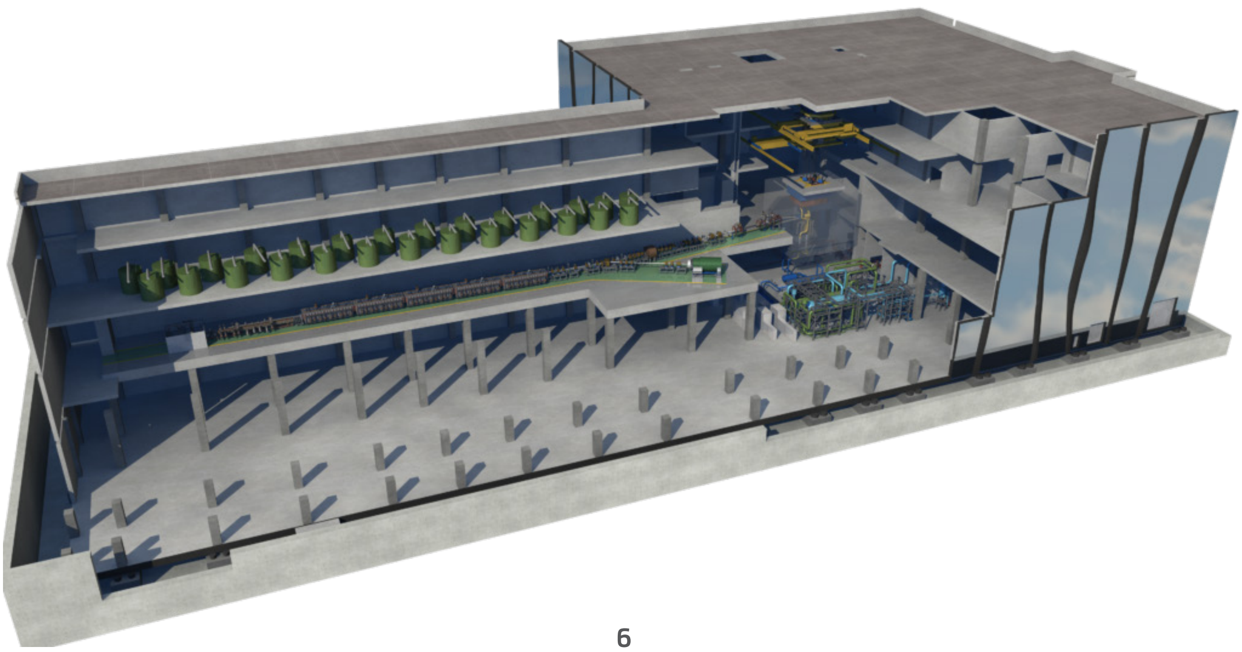
Materials: The Foundation of Everything

The structural materials of a fusion reactor must withstand extreme conditions of temperature, pressure, and—above all—irradiation from fast neutrons, which cause unique cumulative damage compared to fission. It's not enough to find individual materials; what's needed are complete material systems—with coatings, joints, and combinations—that function in an integrated way. Currently, the only viable structural material is RAFM steel, although more advanced materials are already being researched. Experts also stress the need for tests that reach the "end of life" of components—something that has not yet been achieved in any complete nuclear subsystem.

IFMIF-DONES – The Gateway to the Materials of the Future

The IFMIF-DONES project (International Fusion Materials Irradiation Facility – DEMO-Oriented Neutron Source) is one of the most important scientific infrastructures for the future of nuclear fusion. It is being built in Granada (Spain) and will be the only facility in the world capable of testing materials under radiation conditions equivalent to those inside a fusion reactor.

It is expected to begin operations in the 2030s, becoming a cornerstone in the path toward commercial fusion energy.



The Tritium Cycle: The “Elephant in the Room”

Several experts pointed out that **tritium management is one of the most underestimated yet critical challenges.** It is a scarce element, highly permeable, and poses significant safety and regulatory concerns due to its radioactivity. To achieve an operational fusion plant, it is essential to design a closed fuel cycle from the start, including production, storage, purification, recycling, and tritium containment. These systems have not yet been fully validated in an integrated way, and their development will be key to converting prototypes into real power plants.

Tritium in Nuclear Fusion – Where Does It Come From and How Is It Managed?

Tritium (^3H) is a radioactive isotope of hydrogen and a key fuel for the most viable near-term fusion reactions, such as deuterium-tritium (D-T). However, it does not occur naturally on Earth in significant quantities—its half-life is short (~12 years), and it decays quickly.

Today, tritium is produced as a byproduct in certain fission reactors (notably CANDU reactors in Canada), but current global production is very limited: civil stocks total about 25 kg, with only about 2 kg added per year, and reserves are decreasing by ~5% annually due to decay.

In future fusion reactors, tritium will need to be produced in situ through a closed fuel cycle. This requires a key reactor component: the breeding blanket, which surrounds the plasma chamber and contains lithium. This blanket is bombarded by high-energy neutrons from the plasma.generados en la fusión, reacciona para

The tritium produced in this way is extracted, purified, stored, and re-injected as fuel, forming a closed tritium cycle. The efficiency of this cycle is critical: the reactor must produce at least as much tritium as it consumes in order to be self-sufficient.

Creating reliable systems for this cycle will require overcoming major engineering, safety, and regulatory challenges: tritium is scarce, costly, permeable to many materials, and radioactive. That’s why it is often called one of the most important technical bottlenecks on the road to commercial fusion.

The Blanket: Three Critical Functions in One System

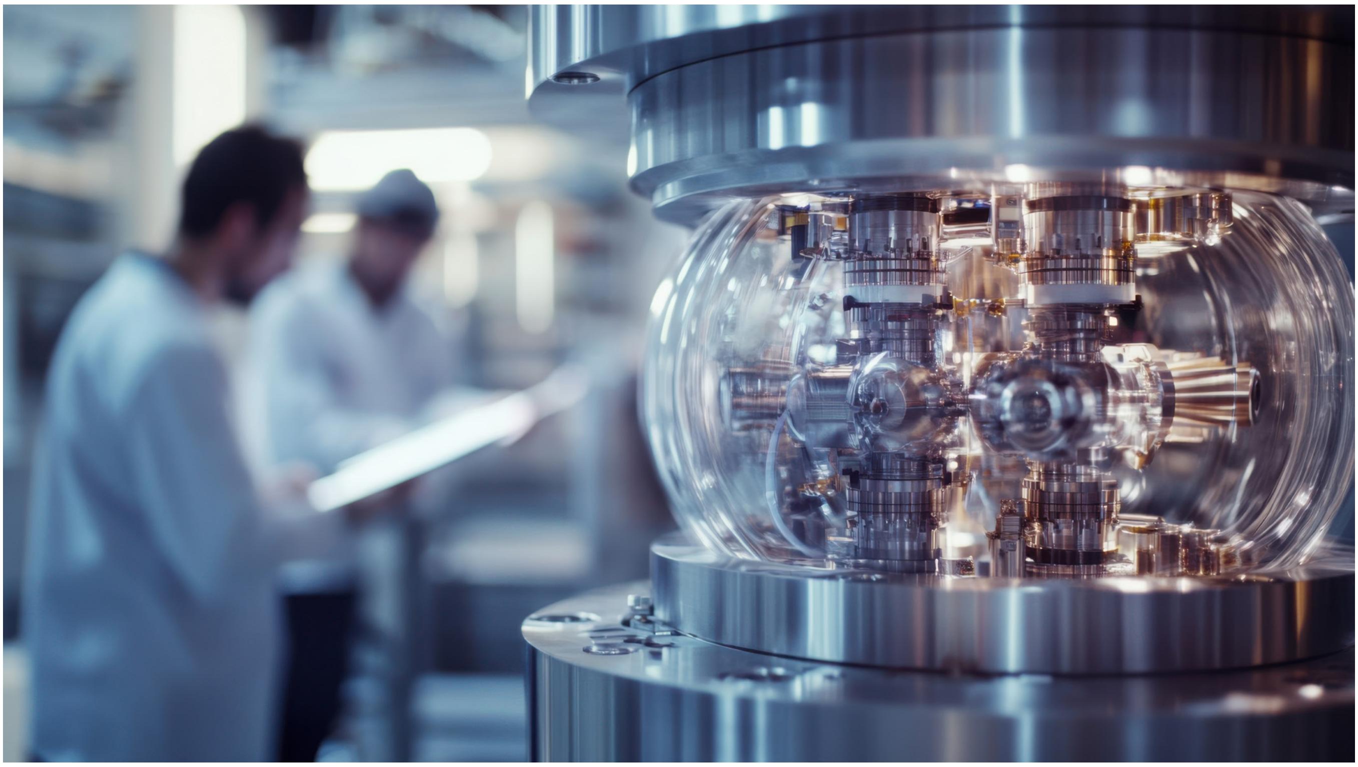
Several experts highlighted the essential role of the breeding blanket, which must simultaneously fulfill three functions: protect the reactor's magnets and structures, extract heat to convert it into energy, and produce tritium through nuclear reactions with lithium.

Despite its central role, no complete tests have yet validated it under operational conditions. It was also noted that the neutrons generated by fusion have an energy (~14 MeV) much higher than those from fission, requiring new structural and thermal engineering solutions.

Robotics and Artificial Intelligence: Operating Without People Inside

Future reactors will need to operate in environments incompatible with direct human presence. Various experts emphasized the urgent need to develop advanced remote maintenance and robotic systems, capable of performing complex tasks with precision and control.

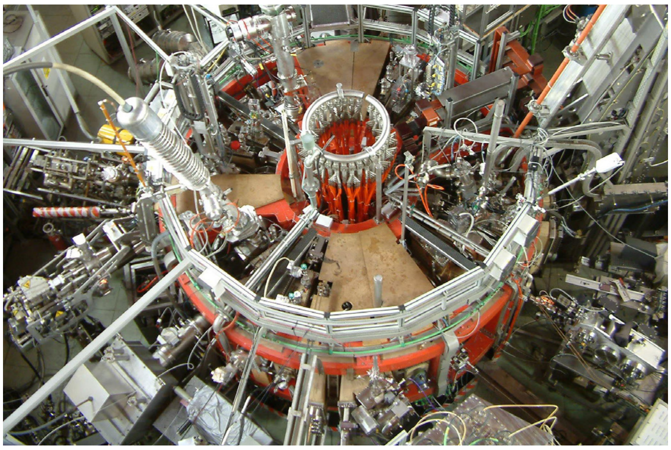
They also highlighted the potential of artificial intelligence to accelerate design, simulation, and predictive maintenance of fusion systems, as well as the importance of shared data platforms and modeling tools to support widespread adoption. Along the same lines, the importance of importing talent and standards from other sectors—such as aerospace and particle accelerators—was stressed, due to their high requirements in precision, reliability, and remote control.



A Shift in Experimental Approach

Many experts agreed on the need to invest in more compact and versatile test facilities, capable of testing components with greater agility and extrapolating results to plant-scale conditions.

In this regard, the **CIEMAT National Fusion Laboratory** plays a central role: its TJ-II stellarator, a highly flexible device capable of adjusting its magnetic configuration on demand, has long served as a testbed for advanced diagnostics, materials transport studies, and wall material development for over two decades.

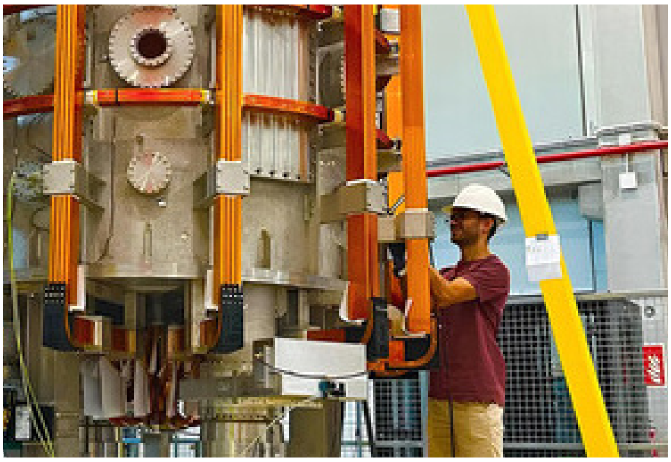


Stellarator TJ-II, CIEMAT.

IFMIF-DONES, mentioned previously, is also one of the key facilities that will support the development of fusion energy in Spain.

IFMIF-DONES.

In parallel, the **SMART spherical tokamak**, developed by the University of Seville, recently succeeded in producing its first plasma. Focused on exploring negative triangularity plasma geometries, it complements this strategy by providing a compact environment to test disruptive configurations through very rapid learning cycles.



SMART spherical tokamak, University of Seville.

However, there is still open debate about whether these testbeds can reliably replicate the extraordinarily complex conditions of a demonstration reactor. Determining the optimal combination of facilities and validation protocols is therefore essential. **The question of how to guarantee robust design decisions remains central to shaping the roadmap toward future commercial fusion plants.**

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A Shift in Experimental Approach

One of the forum's key messages was the need for fusion to learn from sectors that have overcome similar complex technological challenges. The accumulated experience in fields such as space exploration, nuclear energy, civil aviation, or aerospace industry offers valuable lessons on how to scale disruptive technologies, manage regulatory risks, and build supply chains from the early stages.

One participant explained how NASA had to redesign the regulatory framework from scratch to allow commercial players like SpaceX to enter. Over two years, public and private teams worked together to revise each technical standard—maintaining safety without enforcing outdated requirements. "Allowing for equivalencies was key to enabling innovation without breaking the rules," they said.

Another speaker described the design and assembly of major facilities like JT-60SA, emphasizing the vital role of collaboration between industry and research centers to solve technical problems in real time. They called for early industry involvement and stressed the complexity of scaling up components from research to industrial manufacturing. Participants insisted that "design must be sufficiently mature before construction starts" and highlighted the importance of quality control throughout a globally distributed supply chain.

Experts also emphasized the need to integrate aerospace engineers, accustomed to working in vacuum and high-precision environments, with those from nuclear fusion, more used to large infrastructures but with fewer constraints on size and compactness.

At the end of the session, participants agreed that technological learning and open collaboration between public and private institutions—like with the International Space Station—could inspire fusion. "What we're building isn't just a reactor, it's a global cooperation project that can help shape humanity's future."

Technologies with Impact Beyond Fusion

One of the most relevant ideas from the forum was that fusion-driven technologies are already giving rise to innovations with industrial applications far beyond fusion itself. These spillover effects could accelerate return on investment, mobilize industrial sectors, and support Europe's technological sovereignty.

High-potential technologies for transfer

High-temperature superconductors and advanced cryogenics, essential for fusion, also have medical applications (MRI, proton therapy), energy storage, and transportation (magnetic levitation trains).

One participant explained how Japan led in HTS magnets, driving production and opening new uses. Others noted that South Korea and China are now investing heavily in this field, while Europe still faces dependency on non-European suppliers.

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Liquid metal handling, initially intended for heat extraction and tritium breeding in fusion, is being explored for Gen IV reactors and industrial cooling systems.

Radiation-hardened electronics and modular power converters, with potential uses in defense, critical infrastructure, space, and advanced electric grids.

AI, digital twins, and robotics for remote reactor operations, with strong synergies in industrial automation, healthcare, and logistics.

Key Sectors and Stakeholders

Energy (advanced fission, hydrogen, electric grids)

Health (medical imaging, particle therapy)

Defense and aerospace

Transport (rail, aviation, automotive)

Big Science (accelerators, experimental facilities)

Key players in this transfer would include engineering firms, system manufacturers, laser and cryogenic equipment providers, and defense contractors.

Public–private collaboration is seen as essential to scale up these innovations, and Europe must lead in building its own supply chains, especially in magnets and superconductors.

Barriers and Opportunities

Low technological maturity in many areas (low TRLs)

Lack of European suppliers for key technologies like HTS

Shortage of test platforms and industrial validation tools

Experts called for coordinated action, industrial roadmaps, and demonstration programs to accelerate adoption—even before commercial fusion is a reality.

Supply Chain

The commercial rollout of fusion will not depend solely on solving physics or design challenges. Building industrial-scale plants will require a robust, agile, and coordinated supply chain—something not yet fully in place.

As one participant noted: “There is no supply chain yet for many of fusion’s critical components,” and demand uncertainty keeps industry from committing investments.

One supply chain? No—many.

Experts emphasized that there is no single supply chain for fusion, but rather multiple interdependent networks tied to each technological pillar: magnetic confinement, inertial confinement, and laser systems.

However, there are key shared elements: resilient materials, tritium management, remote maintenance systems, radiation-hardened electronics, breeding blankets, and thermal conversion components.

In the case of magnetic confinement, high-temperature superconducting magnets, microwave plasma heating systems, and divertors resistant to extreme heat fluxes stand out. In the case of inertial confinement, the challenges focus on the large-scale production of fuel pellets and on high-precision injection systems.

Uncertain Demand, Frozen Investments

Some experts agreed that without a clear signal of sustained demand, companies will not invest in industrial capacities. Most current suppliers can only produce unique parts in very small series, at high prices and without guarantees of continuity. The experience of Tokamak Energy shows that today's global industry only responds to one-off orders.

In addition, technological uncertainty blocks decisions: if it is unclear which designs will be viable, what technologies will be required, or what standards components must meet, it is difficult to plan factories or logistics chains in the long term.

The Role of Industrial Policy

Experts called for programs based on "milestone-based cost share," such as the model applied in the U.S., where the government sets technical milestones and funds companies that meet them. This creates predictable demand and facilitates private capital mobilization.

They also highlighted the need to choose two or three priority technology concepts to concentrate resources and avoid fragmentation. This does not exclude other approaches but helps define industrial standards and common requirements for

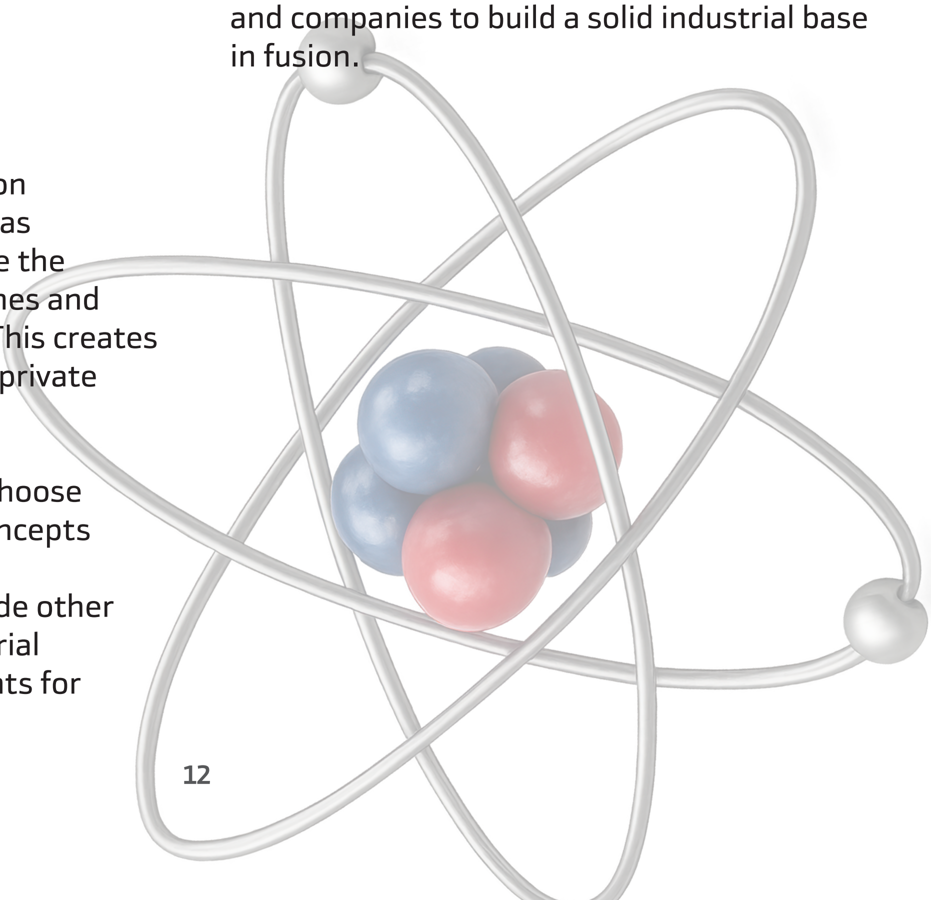
Stronger Public–Private Relationships

Beyond the technical challenge, the forum stressed the need to strengthen trust and long-term alignment between the scientific and industrial worlds. The role of companies as a cross-cutting agent in this process was underlined, as well as the need to define specific standards for the fusion sector, rather than copying those from other industries.

One expert noted: **"The difference between what we hope for and what is truly achievable can only be bridged with trust."** This requires adapting quality standards like the EU's to fusion-specific challenges.

Another expert highlighted that the success of Spain in major projects like ITER and IFMIF-DONES is due to an industrial ecosystem that has been organized for 30 years to support scientific projects.

They called for continuity in this model of cooperation between industrial associations and public research centers and for strengthening dialogue between governments and companies to build a solid industrial base in fusion.



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Key Factors to Accelerate Fusion

Fusion is becoming a systemic innovation challenge that requires close collaboration between public and private sectors, from large labs to startups, engineers, investors, regulators, and talent providers. Its development demands a rethink of governance, financing, training, and regulation.

During the forum, three key pillars were identified to build an effective collaboration ecosystem:

Milestone-oriented investment.

A shared vision to attract and train technical and industrial talent.

A regulatory framework tailored to fusion's specificities.

Investment

Fusion's future depends on financial models that can support development over time. The forum emphasized the need to strengthen public–private partnerships, combining long-term public vision with the speed and innovation of the private sector.

Many experts stressed that current fragmented public R&D funding models are not sufficient to scale fusion, and called for a pan-European project approach that combines public-private collaboration with industrial-scale planning and clear objectives.

It was also highlighted that the **private sector must take a lead role, but needs a better understanding of the risk.**

Participants called for frameworks that encourage private investment without abandoning the public mission, including innovative tools like pre-commercial procurement, co-funding agreements, and clear policies on intellectual property.

Venture capital investors present at the forum noted that fusion has great potential to attract private finance, but it must speak the language of funds. One expert said, "You can't ask investors to wait 30 years for a return." The industry must identify sustainable medium-term business models, with scalability and clear milestones.

Another noted that many investors don't understand the sector's dynamics and demanded more transparency and technically grounded pitches.

In this context, **the forum proposed hybrid investment models that combine public and private funds, with professional risk management and performance metrics comparable to any other deep tech field.**

The key message: investment is not the obstacle—uncertainty is. Fusion needs predictable regulation, clear tech roadmaps, and demonstration of industrial scalability to attract capital that can take it from the lab to the market.

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Talent

Fusion's transition to a commercial, scalable reality will require a new generation of highly skilled professionals.

The scale of the challenge is such that, according to one expert, hundreds of thousands of trained workers will be needed in the coming years, including technicians, engineers, operators, and scientists.

Unlike other tech industries, fusion largely falls within the field of classical engineering, so many roles can be filled by existing profiles (mechanical, electrical, applied physics) with complementary and practical training programs.

Universities are not currently equipped to respond quickly to this demand due to structural and budget constraints. The need to establish public-private partnerships that allow professionals to train from graduate to doctoral levels was highlighted, along with programs for professional retraining and lifelong learning. It was also noted that universities should compete for talent with other, more established STEM disciplines.

Experts agreed that the system must undergo a paradigm shift, acknowledging different skill levels: from the "users" who will operate the plants to the "developers" designing the fusion systems.

Training must also reach developing countries, where much of the new energy capacity will be built in the coming decades.

Speakers also addressed the role of artificial intelligence (AI) in this transition: not only as a tool for technological acceleration but also as a key skill for future professionals. It is already common for new PhDs in fusion to use AI techniques in their research, and this trend is expected to grow.

Regulation

A suitable regulatory framework will be key to accelerating fusion's arrival as an energy source. One shared view at the forum was that we cannot extrapolate from fission regulation to fusion.

According to experts, overly prescriptive regulatory frameworks can hinder and over-bureaucratize development without improving safety: "Regulation must focus on safety objectives, not on overly detailed procedures."

Many warned against repeating past mistakes where excessive requirements increased costs by treating components as if they were nuclear, even when they were not.

Participants agreed that fusion should eventually provide its own licenses and proposed harmonizing international regulations, following a model where licenses are mutually recognized across countries.

This strategy would facilitate commercialization, especially in countries with limited regulatory capacity. In that sense, one expert stressed the importance of performance-based frameworks over rigid requirement lists.

Others emphasized the importance of adopting lessons from other industries—like aerospace or automotive—and training professionals not only technically, but also in regulatory and operational processes. As one participant summarized: "Fusion needs pilots capable of solving equations."

Although fusion entails higher interaction and analysis demands, regulations must adapt to diverse designs and emerging technologies. One speaker noted that designs should facilitate regulation, minimize tritium inventories, and reduce risks related to coolants and materials.

However, others warned that excessively lax regulations in early phases may generate future problems. As one participant said, "even if unlikely, an accident could undermine public and political support for fusion." Hence, integrating safety considerations early in the design phase is key to ensuring long-term regulatory viability.

In summary, fusion needs a regulatory framework that balances agility and stringency, adapting to real risks and evolving with the technology. Most importantly, it must give governments and investors the certainty to move forward without jeopardizing public safety or the sector's future.

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Time Horizons

One of the most frequently asked questions at the forum was when fusion will become a real source of electricity in the global energy mix. On the one hand, startups in the sector, including some at the forum, project functional reactors in under a decade, thanks to agile methodologies, growing private investment, and more compact designs.

On the other hand, experts with decades of experience in large projects highlighted the unresolved technical, regulatory, and logistical challenges. While there's no single answer, the general consensus was that we're entering a new phase, where the first technological demonstrators will be feasible in the next decade. Many participants believe fusion energy could start being supplied to the grid before 2045.

To make this promise a reality, it will be essential to have a clear strategy, sustained funding, and international collaboration that includes effective public-private partnership schemes from the outset.

Only by combining the dynamism of the private sector—with its long-term vision—and the structural capacities of the public sector will it be possible to transform scientific advances into a safe, scalable, and operational energy infrastructure. Fusion is no longer just an idea for tomorrow: it's a project in motion, and this is the time to define its role in the energy transition.