

STRATEGIC RESEARCH & INNOVATION AGENDA **FUSION ENERGY IN EUROPE** **2026**



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The Strategic Research and Innovation Agenda (SRIA) was developed under the Coordination and Support Action GO4FUSION (Project ID: 101212737 — GO4FUSION — HORIZON-EURATOM-2024-NRT-01), incorporating input from the Core Group of the European Fusion Stakeholder Platform (EFSP).

In the future, the SRIA will be managed by FUSION NOW, in agreement with the European Commission (EC).

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**1. EXECUTIVE
SUMMARY**

Scaling fusion from experimental devices to commercial power plants presents a major scientific and technological challenge. To accelerate fusion commercialization, a core priority of EU fusion policy, the EU must address critical technological gaps, such as fusion-relevant materials, tritium breeding, and remote handling. To overcome these challenges, the EU must secure sustained, targeted investments that actively engage industry as a key partner, foster a dynamic innovation ecosystem, and align with a cohesive strategic framework to guide progress.

The Strategic Research and Innovation Agenda (SRIA) will serve as this framework, designed to underpin a future co-programmed Public-Private Partnership (PPP). It will drive fusion energy research and technology from conception to commercial readiness. As outlined in this document, the SRIA aims to identify key enabling technologies for fusion, determine current Technology Readiness Levels (TRLs), assess industry interests, and define fusion research and innovation priorities to guide future R&D efforts in the EU, in alignment with the EU Fusion Strategy.

The SRIA is built on constructive input from the entire fusion community, ensuring that all stakeholder perspectives are incorporated into strategic planning. Given the evolving fusion landscape, it will be periodically revisited and updated to maintain its relevance and to effectively address emerging challenges and opportunities.

The SRIA provides a strategic framework that, through inclusive stakeholder engagement, targeted investments, and project-driven execution, will enable the EU to address critical technological challenges, accelerate the commercialization of fusion energy, and solidify its position as a global leader in next-generation clean energy technologies.

2. Keywords

Fusion technology gaps; power plant; tritium; breeding blankets; power exhaust; diagnostics and control; magnets; cryogenic; plasma heating; targets; lasers; training; knowledge transfer

3. Abbreviations and acronyms

<u>ACRONYM</u>	<u>Description</u>
ARC	Advanced Reactor Concept
BB	Breeding Blanket
BEST	Burning Plasma Experimental Superconducting Tokamak
CERN	European Organization for Nuclear Research
CFEDR	China Fusion Engineering Demonstration Reactor
CRAFT	Comprehensive Research Facility for Fusion Technology
D&C	Diagnostics and Control
DEMO	Demonstration Fusion Power Plant
DoE	Department of Energy
EAST	Experimental Advanced Superconducting Tokamak
EC	European Commission
ECRH	Electron Cyclotron Resonance Heating
EFSP	European Fusion Stakeholder Platform
ELI	Extreme Light Infrastructure
ENSREG	European Nuclear Safety Regulators Group
ESRF	European Synchrotron Radiation Facility
EUROFER	European Reduced Activation Ferritic-Martensitic steel
F4E	Fusion for Energy
FOAK	First Of A Kind

FW	—	First Wall
HL-4	—	High-Temperature Superconducting Tokamak
HTS	—	High Temperature Superconductors
ICF	—	Inertial Confinement Fusion
ICRH	—	Ion Cyclotron Resonance Heating
ILA	—	Industry-Led Association
ITER	—	International Thermonuclear Experimental Reactor
JET	—	Joint European Torus
JT-60SA	—	Japan Torus 60 Super Advanced
K-DEMO	—	Korean Demonstration Fusion Reactor
KPI	—	Key Performance Indicator
KSTAR	—	Korea Superconducting Tokamak Advanced Research
LHCD	—	Lower Hybrid Current Drive
LMJ	—	Laser Mégajoule
LT	—	Long Term
LTS	—	Low Temperature Superconductors
MCF	—	Magnetic Confinement Fusion
MT	—	Medium Term
NBI	—	Neutral Beam Injection
NIF	—	National Ignition Facility
PPP	—	Public-Private Partnership
R&D	—	Research and Development
R&I	—	Research and Innovation
RAMI	—	Reliability, Availability, Maintainability, Inspectability
RF	—	Radio Frequency
SENJU	—	High-repetition-rate laser system
SG-III	—	Shenguang-III laser facility
SMEs	—	Small and medium-sized enterprises
SRIA	—	Strategic Research and Innovation Agenda
ST	—	Short Term
TDP	—	Technology Development Programme
TRL	—	Technology Readiness Levels
VNS	—	Volumetric Neutron Source
W7-X	—	Wendelstein 7-X stellarator
WEST	—	Tungsten (W) Environment in Steady-state Tokamak

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**4. OVERALL
CONTEXT**

4.1. Status of fusion energy development

Fusion, the process that powers the Sun and stars, offers a safe, zero-emission energy source essential for our transition to large-scale, sustainable power. It uses abundant fuel—primarily deuterium, extracted from seawater, and tritium, bred from lithium—producing nearly four million times more energy per unit mass than oil or gas without emitting CO₂. Fusion generates no high-level, long-lived radioactive waste and carries minimal risk of accidents, as the process inherently stops if disturbed. It has the potential to provide continuous baseload electricity, replacing fossil fuels and operating independently of weather conditions and geographic location. Fusion energy could be transformative in the effort to provide a near-limitless, zero-carbon power source.

Fusion energy has been under development worldwide for several decades. Two main approaches are being investigated: magnetic confinement and inertial confinement. The first method uses strong magnetic fields to confine the fusion fuel, while the second compresses a small pellet containing fusion fuel to extremely high densities using powerful lasers. A range of magnetized target fusion systems is also under development.

Thanks to continuous effort and strong international collaboration, key fusion performance parameters have increased by several orders of magnitude, and many breakthroughs have been achieved—particularly in recent years—bringing us closer to the point where fusion power can be commercialized. Fusion energy breakeven has been achieved and exceeded (target gain of around 4) in inertial fusion at the National Ignition Facility (NIF, US), and a fusion energy record of 69 MJ has been obtained at the Joint European Torus (JET, UK) in operations at a factor 2.5 close to power breakeven. The construction of ITER, the international fusion experimental reactor designed to produce 500 MW of fusion power with a gain of 10, has spurred the development of key fusion technologies, such as superconducting magnets with unprecedented performance and size, and components exposed to high-power and particle-flux environments.

However, key design and integration challenges remain. A fusion power plant combines plasma physics, nuclear engineering, materials science, power engineering, and additional competencies into a single, highly complex system. While the underlying concept is well established, achieving reliable and economically viable

operation requires overcoming substantial design and integration challenges across multiple disciplines.

The recent record achievements in fusion energy production—through both inertial and magnetic confinement—demonstrate the potential of fusion as an energy source. The field now faces both opportunities, driven by new scientific insights and technological innovations, and challenges that must be addressed to realize practical fusion energy. Fusion is gradually transitioning from a science-driven endeavor into an energy-value-driven strategy, with a clear focus on delivering practical power to society. Establishing a competitive fusion power industry, however, requires more than the development, demonstration, and deployment of fusion energy technologies. To accelerate and scale fusion energy, we must unite public and private sector talent, expertise, and resources.

Europe has established global leadership in fusion through the successful JET experiments, its central role in the ITER project (providing 45% of construction funding), and sustained efforts under the Euratom Program. However, to maintain this competitive lead in the global race for commercialization, the EU is called to implement a comprehensive and unified fusion strategy.

4.2. Fusion initiatives: international landscape

"Countries are formulating dedicated fusion policies, companies are selecting sites and designing the first generation of power plants, and regulatory bodies are beginning to issue tailored guidance. [...] This convergence of scientific progress, commercial interest and policy attention marks a decisive shift: fusion energy is entering a new phase of real world implementation."

Cit. IAEA, World Fusion Outlook 2025

In a dynamic, fast-evolving global landscape, fusion energy development is experiencing unprecedented momentum, driven by major scientific advances and a significant increase in public and private investment. This momentum is further reinforced by recent breakthroughs at the most advanced fusion facilities, as highlighted in the IAEA World Fusion Outlook 2025 edition.

In the field of magnetic confinement fusion, important milestones demonstrating significant progress in controlling the confined plasma have recently been achieved. In addition to the JET results mentioned above, these include a 1.8 GJ energy turnover during a 360-second plasma pulse on the Wendelstein 7-X (W7-X) stellarator in Germany, the sustainment of high-confinement mode (H-mode) operation for 1,066 seconds on the EAST tokamak in China, and, more recently, a 1,337-second plasma with 2.6 GJ of energy injected on the WEST tokamak in France. The construction of ITER, whose main objectives are to demonstrate the ability to generate and control a burning plasma for several minutes and to produce fusion power of several hundred megawatts, has delivered the strongest performance to date as assembly progresses. The project is now advancing on a stable trajectory, with plasma start-up planned for 2034 and a plasma burning phase in the following decade.

In the field of inertial confinement fusion, the National Ignition Facility (NIF) in the United States has achieved a target gain of 4 across successive indirect-drive ignition experiments, with a record fusion yield of 8.6 MJ from 2.08 MJ of laser energy. The Laser Mégajoule (LMJ) facility in France, the only facility in

Europe capable of delivering energy on the order of megajoules, is progressing towards its design capacity of 1.3 MJ laser energy. Additionally, the Institute of Laser Engineering at Osaka University in Japan has made significant progress by achieving 100 J pulses at 100 Hz on the SENJU laser—an important step toward high-performance lasers with high repetition rates, a crucial element for inertial fusion approaches.

In parallel, emerging national policies are evolving alongside new industrial opportunities. Overall, the combination of scientific progress, increased commercial interest, and heightened political attention marks a decisive turning point: fusion energy is entering an era of practical implementation. However, the path to commercial fusion power plants remains challenging and requires sustained efforts in both fundamental and applied research, as well as technological development. While global players in fusion—primarily in the public sector—have focused their strategies on the construction and operation of ITER, along with accompanying programs in key areas of physics and technology, a new scientific and industrial ecosystem has rapidly developed, encompassing laboratories and research institutions, start-ups, and industrial suppliers.

The race toward fusion energy is now progressing along multiple paths, reflecting the diversity of technologies, approaches, and regional contexts. This development is transforming the European landscape, where world-leading expertise has been built under Euratom—notably through national fusion laboratories and the EUROfusion consortium over the last decade—and where the industrial ecosystem

has been largely driven by ITER construction, with F4E contracting with industries and research organizations to deliver EU contributions. Countries such as China¹, the United States², the United Kingdom³ and most recently Germany⁴, have already launched highly ambitious national projects, while Japan⁵ and Korea are updating their roadmaps considering⁶ significant inflections. Most international roadmaps aim to accelerate the maturity of fusion technologies; however, the strategies of various public and private stakeholders can differ significantly. Most private initiatives aim to deliver a prototype in the early 2030s (e.g., Commonwealth Fusion Systems in the United States), while ambitious public programs (such as in the United Kingdom) aim to have prototypes operational by around 2040. In the case of the EU, the plan is to build two key enabling infrastructures - one for Magnetic Confinement Fusion (MCF) and one for Inertial Confinement Fusion (ICF) -⁷ by 2034 (Section 5.4). In addition to the studies carried out in the European Union by the EUROfusion Consortium, dozens of fusion plant concepts (based on magnetic or inertial confinement approaches) are currently at various stages of development by individual governments, private companies, or joint public-private ventures in Canada, China, Germany, Israel, Japan, the Russian Federation, South Korea, Sweden, the United Kingdom, and the United States. In particular, China has made

fusion a national priority, with more than €1 billion in annual capital investment and the goal of commercialization by 2050. To this end, China has launched multiple projects in parallel with ITER: the CRAFT fusion technology R&D center in 2025 (Hefei), the Yongxing campus under construction (Chengdu), the BEST tokamak (D-T plasma operation, 2027–2045), the CFETR tokamak (power generation demonstrator by 2035), and the high-temperature superconducting tokamak HL-4, currently in its design phase in Shanghai. China also operates the SG-III laser facility, a major laser driver for inertial confinement research (with a 180 kJ laser energy capacity). Japan commissioned JT-60SA in 2023, in collaboration with the European Union under the Broader Approach agreement, supporting ITER and the preparation of its electricity generator demonstrator by 2035, as described in the 2025 update of its national Fusion Energy Innovation Strategy. South Korea operates KSTAR, is considering developing a new compact fusion device, and is preparing the electricity generator demonstrator K-DEMO, aligned with the 2040 timeframe. In the United States, major projects such as those of CFS (with SPARC and the ARC electricity generator demonstrator projects) benefit from significant private funding, which has led to the emergence of more than a dozen start-ups. A fusion power plant concept based on laser-driven inertial confinement is also under development at Longview

1 [The IAEA World Fusion Outlook 2025 edition](#)

2 ["Fusion Science & Technology Roadmap"](#), US Department of Energy, October 2025

3 ["The UK's Modern Industrial Strategy"](#), UK Government, June 2025; ["A New Energy Revolution, The UK's Plan for Delivering Fusion Energy"](#), UK Government, March 2026

4 ["Fusion Energy Action Plan"](#), Federal Ministry of Research, Technology and Space, October 2025: [Fusion - Fusion - BMFTR and Deutschland auf dem Weg zum Fusionskraftwerk](#)

5 ["Fusion Energy Innovation Strategy"](#), Prime Minister Cabinet Office, June 2025

6 ["2026 Nuclear Fusion Research and Development Implementation Plan"](#), Ministry of Science and ICT, January 2026

7 According to the EU Fusion strategy, under preparation at the time of writing

Fusion Energy Systems, building on ignition breakthroughs achieved at the NIF. Significant progress has also been made at the Omega laser system facility at the University of Rochester, a key facility aiming to demonstrate and further understand the physics of laser direct drive (with a 30 kJ laser energy capacity). The US ecosystem is also supported by increased public funding from the Department of Energy (DoE), which backs technological innovation and recently released the United States Fusion Roadmap and Build-Innovate-Grow strategy. Within the European Union and at the national level, Germany is one of the most active countries in the fusion field, with both stellarator-based and target compression fusion plant concepts under development.

Global private investment in fusion reached €9.9 billion on 10 June 2025¹. This growth is highly concentrated, with the United States and China accounting for 85% of funding, creating a competitive landscape dominated by a few highly capitalized national ecosystems. The United States leads the race, hosting 38 of the 68 private fusion companies and securing 60% of global funding. China, with only six companies, accounts for 25% of global funding due to its highly efficient model. These two dominant models appear to be setting the global pace. Although privately funded fusion initiatives dominate in the United States, the EU's €6.8 billion public investment in the ITER supply chain has established a world-class industrial base. However, the long-term sustainability of these supply chains depends on the future market for fusion technologies and commercial fusion power plants, which represents a major challenge for the EU in the coming years.

1 ["Global investment in the private fusion sector"](#), Report from the F4E Fusion Observatory, 2nd Edition, 2025

4.3. EU Vision and Objectives

Energy independence and security are recognized as strategic priorities for the European Union, which acknowledges the transformative potential of fusion energy to contribute to these objectives.

The EU's vision and objectives for fusion development are guided by the following key considerations:

- **Global leadership:** The EU seeks to establish itself as a global leader in fusion energy through the successful commercialization of fusion technologies.
- **Scientific excellence and technological neutrality:** Building on Europe's strong scientific base and technical expertise—including the experience gained through ITER—the EU will pursue a technology-neutral approach that supports both magnetic and inertial confinement fusion concepts.
- **Bridging research and industrialization:** Strategic priorities focus on closing the gap between research and market deployment. This includes developing dedicated research infrastructures, enabling a robust fusion ecosystem through diversified funding and strengthened strategic autonomy, creating clear regulation and resilient supply chains, investing in skills and education, and ensuring streamlined governance and coordination.
- **Mobilizing investment and industrial capacity:** The commercialization of fusion will require substantial public and private investment. EU financial instruments and State aid frameworks should be effectively mobilized to support technology maturation and scale-up. A Public–Private Partnership for Fusion Energy is foreseen to address urgent industrial bottlenecks. In parallel, the EU will promote the development of two flagship enabling facilities: a magnetic-confinement

Fusion Pilot Plant and an inertial-confinement Ignition-grade Implosion Facility, both designed to validate power plant-scale technologies.

- **Addressing structural gaps:** By tackling shortcomings in funding, infrastructure, and workforce capacity, the EU aims to create the conditions necessary for the timely delivery of commercial fusion power, thereby reinforcing energy sovereignty and global competitiveness.

In this context, coordination and integration among key EU stakeholders should be further strengthened through their active involvement in implementing the EU Fusion Strategy, ensuring coherence and alignment with broader policy objectives and funding priorities.

Taken together, this vision and these objectives form a structured and coherent strategy that not only reaffirms the EU's commitment to fusion as a sustainable, low-carbon energy solution but also strengthens its capacity to lead in the emerging global fusion landscape.

4.4. Developing the SRIA

4.4.1. Objectives, scope and purpose of this SRIA

The Strategic Research and Innovation Agenda (SRIA) constitutes a pivotal instrument for structuring the EU's transition from scientific fusion research to industrial deployment. Conceived as the strategic backbone of the future industry-led Public–Private Partnership (PPP) for fusion energy, the SRIA integrates technological priorities, industrial capabilities, and objectives into a coherent, impact-driven agenda.

Fusion research in Europe has reached a high level of scientific maturity, notably through large-scale experimental infrastructures such as ITER and other advanced European facilities. However, moving from experimental validation to demonstration and commercial deployment requires a step change in approach. In particular, it demands:

- Effective risk-sharing mechanisms between public and private actors
- A coordinated investment framework aligned with the EU industrial strategy

The SRIA addresses this challenge by defining prioritized, sequenced, and measurable objectives across short-, medium-, and long-term horizons. These objectives align with EU research and innovation goals, climate-neutrality targets, and strategic autonomy ambitions. The strategic objectives are articulated around three overarching pillars that collectively define

the direction, priorities, and expected impact of the initiative:

- *Accelerate Fusion Technology Readiness Levels (TRLs).* The goal is to shorten the pathway from experimental prototypes to integrated demonstration power plants by de-risking key subsystems and advancing critical technologies towards industrial qualification.
- *Strengthen EU Industrial Leadership in fusion.* By embedding industry at the core of the PPP, the SRIA ensures that technology development is market-oriented rather than solely research-driven. It fosters supply-chain consolidation, standardization, and the emergence of European industrial fusion technologies.
- *Enable First-of-a-Kind (FOAK) Fusion Power Plants.* The ultimate objective is to make first-of-a-kind fusion power plants technically feasible, economically viable, and investable within a realistic timeframe, thereby laying the foundations for commercial roll-out.

The Long-Term Vision is grounded in a clear and forward-looking strategic ambition:

- Fusion as a sustainable, safe, and competitive energy source contributing to Europe's climate neutrality and energy security.

The scope of the SRIA is structured around the system-critical building blocks required for commercial fusion deployment. These correspond to the key technological gaps described in Section 5.3 and encompass the full power plant system architecture. This system-oriented

approach ensures coherence between subsystem development, industrial integration, and overall power plant performance targets.

The target audience includes a diverse but strategically defined group of stakeholders:

- Industrial stakeholders (large companies, SMEs, supply-chain actors, system integrators)
- Research and Technology Organisations
- Public authorities and policymakers at the EU and national levels
- Investors and financial institutions seeking structured, de-risked innovation pathways.

The co-programmed Public–Private Partnership (PPP) will serve as the governing framework, enabling:

- Competitive, targeted, co-funded calls for proposals
- Joint industry–research consortia
- KPI-based performance tracking and impact assessment

This governance model (see Section 7) ensures accountability, flexibility, and genuine industrial ownership of the innovation pathway, while maintaining alignment with public policy objectives.

The SRIA represents a transformative step for European fusion energy. By combining industrial leadership, technological prioritization, and long-term system integration, it establishes a credible and structured pathway

from science to commercial power generation. In doing so, it positions the EU not only as a global scientific leader in fusion, but also as a future industrial and commercial leader—aligned with its strategic, economic, and climate ambitions.

4.4.2. Key Performance Indicators

In light of the current status of fusion energy development in Europe and the associated challenges, a set of objectives has been established for the co-programmed Partnership.

The objectives fall into three categories: general, specific, and operational, depending on their scope and timeframe. All three categories are interconnected and subject to a rigorous monitoring framework based on Key Performance Indicators (KPIs). While operational objectives are measured through quantitative technical targets, specific and general objectives use KPIs focused on industrial impact, market capacity, and Europe's technological leadership. These three levels are closely linked, as the technical progress achieved through short-term operational goals directly enables the fulfillment of specific medium-term objectives, which, in turn, collectively drive the realization of the

Partnership's long-term general vision.

General objectives have a long-term vision and should align with relevant EU priorities, strategies, and targets¹. The Partnership aims to support and incentivize the European fusion community and industry to address key bottlenecks and reinforce the EU's technological leadership in commercial fusion energy. Through the Partnership, industry will develop and retain the technologies, components, and processes needed to build a competitive European ecosystem.

The two general objectives are²:

- GO1** *Accelerate technological development towards a grid-connected European Fusion Power Plant*
- GO2** *Build a competitive and sovereign European fusion energy industrial, supply chain and skills ecosystem*

Within the two objectives a set of KPIs has been identified:

- **GO1:**
 - *KPI - GO1: aggregated technology readiness advancement of critical subsystems (% increase³)*
- **GO2:**
 - *KPI1 – GO2: cumulated EU funding*

1 References: i) 2023-2025 Euratom Work Programme ("the Commission aims to support and incentivise the European fusion community and industry [...] This will help industry develop and retain the necessary technologies, components and processes for a competitive European supply chain");

ii) "Euratom Work Programme 2026-2027 for nuclear research and training" ([Euratom Work Programme 2026-2027 for nuclear research and training](#));

iii) The Draghi Report "[The Future of European Competitiveness](#)";

iv) The Commission's study "Analysis on a strategic public-private partnership approach to foster innovation in fusion energy"; v) The Fusion Expert Group (FEG) Opinion Paper

2 The general, specific and operational objectives set out below reflect the overall EU ambition towards delivering commercial fusion energy. It is only expected that the Partnership aligns with these objectives, and contributes to achieving them, in combination with other relevant initiatives, and in line with the timeline and budget set in this document.

3 The '% increase' will be calculated with 100% corresponding to TRL 8. This applies to all KPIs expressed as '% increase'.

(in €) allocated to selected projects under the Partnership's calls

- KPI2 – GO2: valuation of in-kind additional activities (in €)
- KPI3 – GO2: valuation of investments in operational activities (in €)

Specific objectives are medium-term and should be targeted pragmatically. Derived from the general objectives, their formulation is also based on this program's agenda, with particular attention to the identified gap analysis areas. Given its strategic significance, the dissemination of R&D results has been defined as a standalone objective.

- SO1** Strengthening the European fusion energy innovation ecosystem
- SO2** In supporting the development of fusion energy enabling technologies, address the challenges identified in the Strategic Research and Innovation Agenda (SRIA)
- SO3** Communicate, exploit and disseminate results from projects led under the Partnership, focusing on the European fusion energy innovation ecosystem

To track progress towards these objectives, Key Performance Indicators (KPIs) have been developed to monitor the closing of gaps, the advancement of fusion energy companies and projects, and the communication and dissemination activities.

- **SO1:**
 - KPI1 – SO1: number of operational joint industrial test facilities
 - KPI2 – SO1: increase of fusion-related

turnover, investment and expenditure among private companies involved in the Partnership (in %)

- **SO2:**
 - KPI – SO2: aggregated progress on addressing SRIA challenges (in %, 100% = all SRIA challenges addressed)
- **SO3:**
 - KPI1 – SO3: number of peer-review publications resulting from the Partnership
 - KPI2 – SO3: number of in-person and online events organized in the scope of the partnership and corresponding cumulated audience
 - KPI3 – SO3: number of patent applications resulting from the Partnership

Finally, operational objectives are the concrete short-term results of the projects funded and developed with higher priorities along the SRIA, thus relating to what is to be delivered during the lifetime of the PPP. The operational objectives¹, and related KPIs have been developed to track the advancement of actions identified in the SRIA.

- OO1** Develop integrated engineering designs for future fusion power plants ensuring scientific soundness and maximising potential for commercial viability
 - KPI1 – OO1: progress in delivering and demonstrating integrated engineering designs (% increase, 100% = at least one integrated design demonstrated at TRL8)
 - KPI2 – OO1: Develop, advance and deliver integrated modelling and simulation codes for burning plasmas validation (% increase)
- OO2** Advance and demonstrate tritium breeding blanket and first

¹ For OO1 to OO10, the KPIs are meant to aggregate the progress made for each gap at the level of SRIA's actions; For OO1 to OO10, the KPIs encompass systems and subsystems for the considered technologies.

wall concepts and technologies, aiming at tritium self-sufficiency and efficient electricity generation, and optimizing reliability of operation and availability

- KPI – OO2: technology readiness advancement for tritium breeding blanket concepts and technologies (% increase)

OO3 Advance and demonstrate tritium fuel-cycle concepts and technologies able to produce, handle and recycle fusion fuels in a closed loop

- KPI – OO3: technology readiness advancement for tritium fuel-cycle concepts and technologies (% increase)

OO4 Advance and demonstrate diagnostics & real-time control platforms and components, able to ensure high reliability and accuracy of operation, and effectively manage unforeseen transient events

- KPI – OO4: technology readiness advancement for diagnostics & real-time control platforms (% increase)

OO5 Advance and demonstrate magnets and cryogenics concepts and technologies, able to provide magnetic confinement-relevant fields at minimum capital and operating cost

- KPI – OO5: technology readiness advancement for magnets and cryogenics concepts and technologies (% increase)

OO6 Advance and demonstrate plasma power and particle exhaust concepts and technologies, able to manage fusion thermal loads and minimizing adverse impacts on power plants components and quality of burning plasma

- KPI – OO6: technology readiness

advancement for plasma power and particle exhaust concepts and technologies (% increase)

OO7 Advance and demonstrate industrial-grade, efficient and reliable plasma heating systems for steady-state operation of future power plants

- KPI – OO7: technology readiness advancement for plasma heating systems (% increase)

OO8 Advance and demonstrate innovative concepts and technologies for inertial confinement fusion targets

- KPI – OO8: technology readiness advancement for inertial confinement fusion targets (% increase)

OO9 Advance and demonstrate innovative concepts and technologies of high-power lasers and optical technologies for inertial confinement fusion

- KPI – OO9: technology readiness advancement for high-power lasers and optical technologies (% increase)

OO10 Foster the development of material testing for critical components of future fusion power plants

- KPI – OO10: technology readiness advancement for materials challenges identified in the SRIA (% increase)

OO11 Contribute to the consolidation and development of European fusion training & knowledge management programs

- KPI – OO11: number of fusion energy-related training & knowledge programs launched and / or expanded under the Partnership, and corresponding number of trained persons

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**5. RESEARCH &
INNOVATION
PRIORITIES**

A coordinated push to integrate scientific breakthroughs with industrial innovation is required to transition the EU fusion program from laboratory-scale gain to the full commercialization of fusion energy, ensuring the EU's global leadership in fusion energy.

5.1. Introduction to fusion power plant concepts & technologies

Fusion is the process in which light nuclei—such as hydrogen isotopes—combine to form a heavier nucleus. During fusion, part of the reactants' mass is converted into energy according to Einstein's relation $E=mc^2$, which can be harnessed to generate electricity in a fusion power plant. Fusion powers the Sun and the stars.

To achieve fusion, nuclei must be brought sufficiently close together and have enough energy for the strong nuclear force to overcome their electrostatic repulsion. In stars, this is enabled by immense gravitational confinement. On Earth, where gravity is insufficient, fusion requires extremely high temperatures (above 100 million °C). At these temperatures, matter becomes plasma, an ionized gas that serves as the fusion fuel. The most promising reaction is the fusion of two hydrogen isotopes, deuterium (D) and tritium (T), producing a helium-4 nucleus (alpha particle) and a neutron:



The reaction products carry significant kinetic energy: the neutrons escape and deposit their energy in a component surrounding the reaction chamber—called the blanket—where their kinetic energy is transformed into heat and then transferred to a power conversion system to generate electricity; the charged alpha particles remain confined in the plasma and help sustain its temperature by transferring their energy to it. The energy confinement time is defined as the time required for the plasma to lose its energy in the absence of heating by alpha particles or other external sources. For a fusion system to produce more energy than it consumes, the triple product of plasma temperature, density, and energy confinement time must exceed a certain value ($5\times 10^{21}\text{m}^{-3}\cdot\text{s}\cdot\text{keV}$).

Two main approaches are used to reach these conditions:

- **Magnetic Confinement Fusion (MCF).** In this concept, a hot plasma is confined within a vacuum vessel by strong magnetic fields that generate

forces that prevent the plasma from interacting with the vessel walls. The most successful magnetic field configurations for achieving the power plant-relevant plasma conditions are the tokamak and the stellarator, though other concepts are under investigation (such as reversed field pinches, mirrors, and magnetized target fusion):

- Tokamaks. The magnetic field is generated by electric currents flowing in coils external to the plasma and within the plasma itself. Tokamaks have an axisymmetric configuration, which simplifies their design. However, the presence of the plasma current makes them more prone to disruptions.
- Stellarators. The magnetic field is produced primarily by twisted external coils. Stellarators have more complex, non-axisymmetric configurations. By eliminating the need for a large plasma current, stellarators are inherently more stable and can operate continuously.

Tokamaks have historically achieved higher plasma pressure and energy confinement, but advanced stellarators are narrowing the gap through optimized three-dimensional field designs and improved heating schemes.

Current-generation magnetic systems rely on low-temperature superconducting (LTS) magnets, such as those developed for ITER, to generate high-intensity magnetic fields, albeit at extremely low operating temperatures. The deployment of high-temperature superconducting (HTS) materials could enable stronger magnetic fields

while reducing cryogenic cooling requirements, potentially lowering both recirculating power and the overall cost of MCF power plants.

Plasma heating to fusion-relevant temperatures is achieved through electromagnetic waves, high-energy neutral particle beams, and, as the fusion reaction proceeds, with self-heating from fusion-born alpha particles. High-efficiency heating systems are therefore essential, as they directly influence plant performance and net energy output.

In (quasi) steady-state MCF operation, the deposited power must be safely exhausted, while helium ash, impurities, and unburned fuel are continuously removed. This function is performed by divertors—specialized in-vessel components designed to withstand extreme heat fluxes ($\approx 10 \text{ MW/m}^2$)—and, through optimized magnetic configurations, to direct heat and particles towards dedicated target plates. The divertor represents one of the most critical technological challenges for commercial fusion. The so-called “monoblock” concept, based on tungsten target monoblocks on copper alloy cooling tubes, may prove inadequate for a fusion power plant, as neutron irradiation, erosion, and severe thermal loads constrain its operational lifetime. Consequently, advanced divertor designs, magnetic configurations, and high-performance materials are essential to ensure sufficient plant availability and economic viability.

Inertial Confinement Fusion (ICF). Inertial confinement fusion is achieved by using high-energy lasers or intense ion beams to rapidly compress (to densities of several hundred g/cm^3) and heat a small fuel pellet—a tiny spherical fuel capsule—

so that the inertia of the pellet's outer layers temporarily confines the plasma, enabling fusion reactions to occur before the fuel disassembles. There are two schemes in the inertial confinement approach:

- Indirect-Drive Inertial Fusion: The lasers or beams first strike a surrounding cavity called a hohlraum, producing intense X-rays that then ablate the outer surface of a fuel pellet, driving a spherically symmetric implosion that compresses the fuel to fusion conditions. The X-ray bath is more uniform than direct laser beams, making the implosion more stable and robust against non-uniformities in the laser beam. However, this scheme is less energy efficient than direct-drive inertial fusion because only a small fraction of the driver energy entering the target chamber ends up as thermal energy in the capsule—some of the driver energy is lost in the conversion to X-rays inside the hohlraum, and most of the X-ray energy is used to heat and accelerate the ablator.
- Direct-Drive Inertial Fusion: The fusion fuel pellet is hit directly by high-energy lasers or particle beams, which ablate its outer surface and generate a spherically symmetric implosion. This rapidly compresses and heats the fuel, causing the core to reach conditions required for fusion. This scheme—which allows central hot-spot ignition, shock ignition, and fast ignition—is potentially more energy-efficient than indirect-drive inertial fusion because the laser energy is directly coupled to the target.

The recent energy breakeven records were obtained at NIF that has been designed and implemented for an indirect drive scheme. However, apart from low efficiency of this scheme, also the mass production of hohlraum represents a challenge for future ICF power plants. Target characteristics vary between direct and indirect-drive schemes, but capsule quality are of primary importance in both cases. A future ICF power plant will need mass fabrication of high quality, high-efficiency and low-cost targets, metrology, as well as highly accurate target injection and positioning technologies. The other main requirement for a future viable ICF power plant is the availability of the laser systems to ensure at the same time the most efficient coupling to the target (shot per shot) and a sufficient repetition rate to produce a commercially attractive global energy yield. The direct drive scheme requires a new generation of laser sources, with more stringent beam quality specification to avoid the arising of instabilities during the early stages of the implosion. The assessment of a direct drive point design has to be carried out experimentally with the optimal irradiation geometry and state of the art laser and target technologies.

Both MCF and ICF power plants using the DT fuel cycle need to produce the tritium they consume in a self-sufficient way via the ($6\text{Li}, n$) and ($7\text{Li}, n$) reactions using the neutrons released by the (D, T) reaction. This is to be implemented via the so-called tritium breeding blanket (BB), a component to be installed inside the vacuum vessel with an integrated first wall (FW) which is the innermost component facing the fusion plasma. Beside the production of tritium, the breeding blanket must ensure the extraction of fusion energy deposited by

the escaping plasma particles, radiation and fusion neutrons, and the protection of the downstream components (vacuum chamber, superconducting magnets) from the fusion neutrons and secondary radiation. In ICF power plants, where the FW can be a separated component to the BB, it is subjected to X-ray and ion irradiation (implosion debris) that may exceed the neutron load.

The breeding blanket/first wall is the key nuclear component of a fusion power plant. Such components have never been manufactured nor tested in a fusion environment (ITER has only shielding blanket). The current maturity of these technologies is not sufficient to achieve the required performances for a fusion power plant. The current TRL for the complete system is still quite low, which will have to rise up to a high TRL to realize the ultimate goal of commercialization of fusion energy.

The breeding blanket, where tritium is produced and extracted, is part of the fusion power plant fuel cycle system. Though the plasma fueling schemes are inherently different in MCF (continuous DT pellet injection in hot plasma) and ICF (high frequency target production and injection), they have in common other fuel cycle technologies (for T extraction, vacuum pumping, exhaust processing and clean-up, isotope separation, gas and water detritiation, T accountancy).

The optimization and control of plasma performance (in MCF) or target implosion (in ICF), continuous and safe operation, as well as reliable functioning of all plant systems require a minimum set of diagnostics and controls to ensure real-time feedback and machine protection. Although extensive diagnostic systems are used in current experiments to

provide the necessary measurements, the high fluence of plasma particles and neutrons, and radiation loads, the presence of tritium and space limitations in future fusion power plants will impose severe limitations in terms of possible diagnostic implementation. Reliable diagnostic systems, satisfying stringent engineering requirements must be developed to ensure reliable and high-quality measurements.

Above all, a most prominent area of development common to both MCF and ICF, is that of materials capable of withstanding intense fluxes of neutrons, radiation and particles — causing damage and degradation of thermo-mechanical properties — for a sufficiently long period of time to allow full component integrity and plant availability, both necessary for a safe and sustainable commercial operation with reduced generation of radioactive waste. A core requirement for fusion power plant design and operation is the development of qualified advanced materials - structural and functional – and manufacturing technologies for in-vessel components (blanket, divertor), and for diagnostics front-end components.

A fusion power plant combines plasma physics, nuclear engineering, materials science and power engineering into a single, highly complex system. While the underlying concepts are established, achieving reliable and economically competitive operation requires overcoming substantial design and integration challenges across multiple disciplines.

5.2. EU Research and Market overview

The EU fusion landscape is experiencing increasing industrial involvement. European companies are deeply integrated into ITER's supply chains, delivering high-value components such as superconducting magnets, vacuum vessel sectors, remote-handling systems, and high-precision manufacturing solutions. This engagement has significantly strengthened Europe's industrial capabilities in advanced engineering, materials science, and nuclear technologies

The European Union has led the ITER project, the world's largest fusion experiment, through its contributions via Fusion for Energy (F4E). This long-term commitment, representing almost half of ITER's construction cost, has consolidated Europe's leadership as the project's host and laid a robust industrial and technological foundation essential for advancing fusion energy.

EU research and market analyses underscore the EU's leading role and industrial capabilities in fusion technology. Existing EU fusion industry capacity, particularly in high-value technologies, demonstrates Europe's competitiveness through successful contracts and technical achievements, with about 3,000 companies directly or indirectly involved in F4E contracts (as noted in F4E Highlights 2024), and mapped across more than 400 technologies relevant to fusion. Further evidence is provided by the F4E Technology Development Program (TDP), which demonstrates the EU's industrial capabilities to address specific technological gaps¹.

Small and medium-sized enterprises (SMEs) play a critical role within the EU fusion supply chain, providing specialised expertise and driving innovation. Through targeted measures under the F4E partnership, the EU streamlines contractual mechanisms and industrial collaboration. These ongoing actions² strengthen the EU's position in the global fusion market.

Beyond ITER itself, a comprehensive assessment of public and private sector investment in fusion provides an overview of the full scale of the European fusion

programme. This includes EU framework programme funding (e.g. the Euratom Research and Training Programme and Horizon Europe), national contributions from Member States, in-kind industrial participation, and the rapidly growing private fusion investment landscape.

Private fusion initiatives and start-ups are emerging across Europe, often supported by venture capital, national innovation programmes, and EU funding instruments. These actors are exploring different confinement concepts and accelerated development pathways, complementing the public research programmes and contributing to a more dynamic fusion ecosystem.

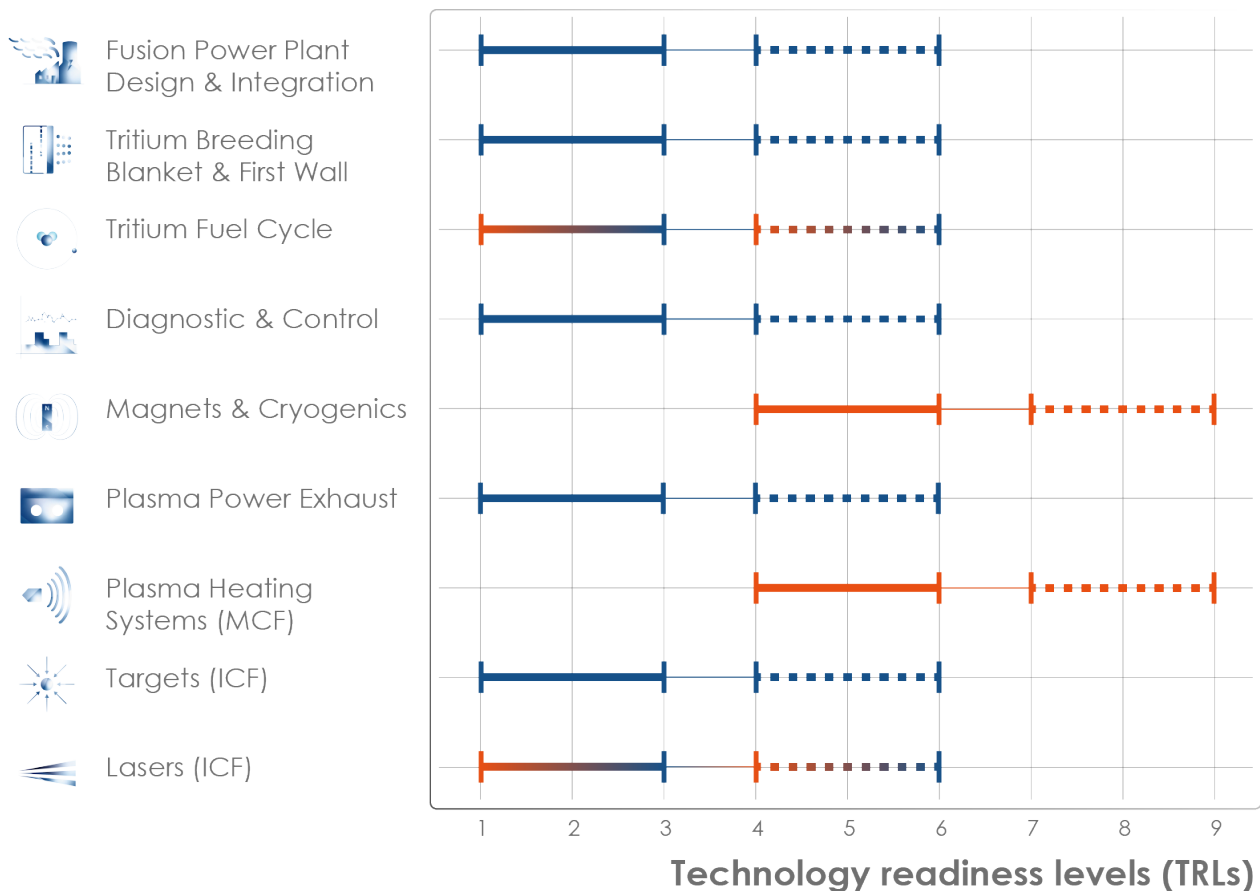
Finally, leading energy companies (such as ENI, RWE, Siemens Energy, and St1) are developing fusion energy, investing resources and exploring partnerships with fusion laboratories and start-ups to advance cutting-edge technologies. Their role as active partners in fusion development will be key for defining commercial requirements, providing resources, developing supply chains, managing grid integration, and transitioning fusion to industrial energy production.

Regarding the contribution to ITER, a 2021 study concluded that the project's return on investment is approximately 1:1. Projections indicate that by 2030, ITER could generate an additional €16 billion in Gross Value Added (GVA) and create over 70,000 job-years³.

1 [F4E TDP Section](#) on F4E Industry Portal, in particular [TDP Reports & Workshops](#), and [TDP Presentations](#)
 2 [F4E Small and Medium Enterprises section](#) on F4E Industry Portal and [SME Scheme](#)
 3 <https://data.europa.eu/doi/10.2833/51838> / F4E report 2025

5.3. Gap analysis & challenges

This section identifies key technological gaps and proposes targeted actions to resolve them, guiding the EU's strategic R&I priorities.

Graph 1. Fusion Technology Gaps & TRLs Progression**GAP****Average time period for the progression of actions across different gaps:**

- Short < 2030
- Short-Medium < 2030-2035
- Medium < 2035
- Long < 2040

TRL Level:

- Present
- Targeted

Key fusion technology gaps, showing current and target Technology Readiness Levels (TRLs) and the indicative time-lines for actions needed to close each gap.

The identified technological gaps are summarized in Graph 1, while the key findings of this analysis are presented in the following subsections and in Tables 1–10. For full details, readers should consult the Technical Annex accompanying this document. They have been identified, building on the achievements and critical analyses of progress yet to be made, according to the European fusion laboratories and in consultation with the community through dedicated meetings. These meetings gather the most comprehensive fusion public and private stakeholder landscape, spanning both magnetic fusion (such as tokamaks, stellarators,

and open/mirror magnetic systems) and inertial confinement fusion, as well as other approaches. Some of these gaps are common to both magnetic (MCF) and inertial (ICF) confinement fusion; addressing them will promote synergies between the two approaches, while fully accounting for their specific differences. In addition, sustained efforts in training and knowledge transfer are recognized as crucial for supporting all aspects of fusion R&D, helping to build the future workforce and foster innovation across the sector. The goal is to maximize synergies between various credible approaches while minimizing the risk of dispersing efforts and resources.

For each identified gap, the problem statement has been summarized, and specific challenges and proposed actions have been outlined. For each technology, Technology Readiness Levels (TRLs) have been assessed according to the following convention:

- “Low TRL” means TRL between 1-3 (from principle to experimental proof of concept). The identified gap is between fundamental research and applied research. Having reached this point, one can conclude that the technology is feasible from a scientific perspective.
- “Medium TRL” means TRL between 4-6. The identified gap is between advanced research and technology demonstration in a relevant environment (from components to prototype). It should be noted that this phase is sometimes referred to as the “valley of death”, due to the very high cost of testing the targeted technology in the operational environment.
- “High TRL” means TRL between 7-9 (from prototype to mass-produced product). The identified gap is in the phase of technological qualification and validation.

Effective coordination of concept development and the advancement of TRL for fusion energy, paired with clearly defined timescales, is essential. These timescales are categorized at three levels:

- Short Term (ST), before 2030
- Medium Term (MT), before 2035
- Long Term (LT), before 2040

This analysis should be pursued further,

with fusion stakeholders aligning their efforts within existing EU legal and financial frameworks to accelerate the transition from basic technology research (TRL 1–2) to system testing and operation (TRL 8–9). In addition to TRLs, each action has been evaluated and assigned priorities based on three additional criteria:

a) *Priority level based on action's contribution to deploying fusion energy:*

1. *Indispensable (critical for deployment)*
2. *Accelerating (speeds up deployment)*
3. *Enabling (expands design space without acceleration)*
4. *Strategic (promotes EU autonomy in fusion science and technology)*

b) *Industry's willingness to invest*

Is the industry prepared to invest its own resources in the action (in kind and/or financial)? (see technical annex)

1. Yes
2. No

c) *Industry participation interest.*

Does the industry intend to participate in the action? (see technical annex)

1. Yes
2. No

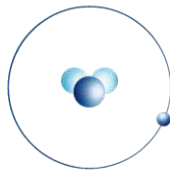
The criteria (TRL and priority) described above and indicated for each action are based on an average of individual responses from participating stakeholders. While this approach provides a consensus-based view, it does not differentiate between stakeholder groups—such as supply chain participants or start-ups—whose expertise, interests, and strategic priorities may vary significantly. Given that MCF and ICF approaches are at different stages of development, the priority levels assigned to actions addressing specific gaps in MCF or ICF should be considered within their specific contexts.



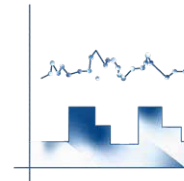
Fusion Power Plant
design & integration



Tritium Breeding
Blanket & First Wall



Tritium Fuel
Cycle



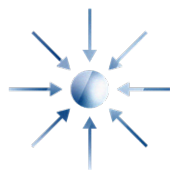
Diagnostic
& Control



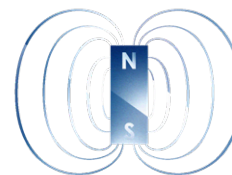
Plasma Power &
Particle Exhaust



Plasma Heating
Systems



Targets



Magnets &
Cryogenics



High Performance
Lasers



Training, Knowledge
Management



5.3.1. Fusion Power Plant design and integration

Problem statement:

Develop integrated engineering designs for a fusion power plant based on credible, research-validated fusion concepts.

These designs must address the high level of interconnection among all components and the complex set of constraints inherent to fusion power plants. In the case of MCF, significant progress has been made on JET with the achievement of high fusion power and record fusion energy, demonstrating a sustained plasma gain of $Q \approx 0.6$ on a seconds-long timescale. On the other hand, long plasma durations (over 20 minutes) with a gigajoule of energy injected and extracted were achieved on the EAST (CN) and WEST (EU) tokamaks, and (over 300 seconds) in the Wendelstein 7-X stellarator (EU). In addition, significant progress has been made in several areas of ITER construction, including superconducting magnets and the divertor. However, significant technological gaps remain and must be addressed for a safe, economically sustainable fusion power plant. Several fusion power plant concepts are available in the literature. While these allow for the identification of important design drivers and the numerous interconnections between different systems (e.g. EU-DEMO), none of these studies have reached the stage that could lead to the construction of a fusion power plant. One of the main reasons is the low maturity of several critical components, such as tritium breeding blankets.

In the case of ICF, fusion power plant

concepts are still in a very preliminary stage. The proof of principle of laser ignition has been provided by the ignition experiments carried out on the NIF, which was never intended as a precursor to an inertial fusion power plant. At NIF, these plasmas are created via indirect drive, with laser beams irradiating a high-Z cavity (hohlraum). By design, the NIF irradiation setup is challenging to achieve the high energy gain required for ICF power plant design, which would instead rely on direct drive (laser beams focused directly on the capsule), as envisioned by the vast majority of the ICF scientific community. Moreover, the physical demonstration that the direct-drive scheme yields the expected simulated gain remains to be achieved, as neither NIF nor LMJ will be able to do so over the next decade.

A viable fusion power plant requires a power gain greater than 30 in the case of MCF, or an energy gain close to 100 in the case of ICF. Currently, the maximum target gain obtained on NIF is around 4. Designing a laser fusion power plant involves identifying an operating point that combines the development of high-performance laser systems, improved target implosion, high-rate operation, and robust, low-cost target manufacturing, together with their injection into the installation's chamber (see gaps below).

Referring to an engineering process that starts with feasibility studies, then moves to conceptual studies, followed by preliminary and detailed designs, and ending with manufacturing plans, current studies for fusion power plants are at best at the conceptual stage for

MCF and at the feasibility stage for other approaches.

To accelerate the transition from achieving fusion energy gain to fully commercializing fusion energy,

it is essential to consider its market affordability. This involves reducing production costs, enhancing energy efficiency, and ensuring the technology is competitive with existing energy sources.

Challenges:

- 5.3.1.1. Achieving a fusion plasma with the necessary parameters for energy production.
- 5.3.1.2. Designing, based on credible fusion concepts, the fusion power plant with the lowest capital and Operation & Maintenance costs, and the highest efficiency and availability.
- 5.3.1.3. Maximizing overall plant efficiency by considering all influencing factors, from blanket temperature to the efficiency of the energy conversion process, the recirculated power fraction, and the lifetime of components.
- 5.3.1.4. Including manufacturability, reliability, availability, maintainability, and inspectability (RAMI); and economic and environmental attractiveness at the early design stage.
- 5.3.1.5. Managing the different levels of maturity of fusion power plant components—which will increase during the design phase—with the potential for innovation or breakthrough unknown at the start-up date (mastering an evolving design throughout its operational life).
- 5.3.1.6. Mastering the high complexity arising from significant interdependencies between the large number of interconnected and complex systems, requiring compromises to tackle contradictory constraints.
- 5.3.1.7. Developing the industrial supply chain for fusion.
- 5.3.1.8. Applying appropriate safety rules to the correct safety cases from the beginning of the design; fusion regulation is not yet stabilized, and there is a risk of over-constraining the design space, given the different nature of hazards.
- 5.3.1.9. Managing reactive power and exchange at the plant level.
- 5.3.1.10. Achieving a continuous and stable supply of electricity to the grid.

Figure 1. Fusion Power Plant Design and Integration — Challenges and Actions Summary



Table 1. Fusion Power Plant Design and Integration — Challenges and Actions

Short Term Actions <2030

Designing, based on credible fusion concepts, the fusion power plant with the lowest capital and Operation & Maintenance costs, and the highest efficiency and availability

- ▲ Develop standards for engineering processes
- ▲ Develop standards for manufacturing
- ▲ Develop standards for quality management

Including manufacturability, reliability, availability, maintainability, and inspectability (RAMI); and economic and environmental attractiveness at the early design stage

- ▶ Develop AI advanced fusion power plants technologies:
 - a) Materials development
 - b) Power plants integration
 - c) Data management
 - d) Quality control

Mastering the high complexity arising from significant interdependencies between the large number of interconnected and complex systems, requiring compromises to tackle contradictory constraints

- ▲ Develop system engineering & integration approach
- ▲ Develop asset integrity procedures (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing devices

Applying the right safety rules to the right safety case and from the beginning of the design; fusion regulation is not yet stabilized and there is a risk to over-constrain the design space given the different nature of hazards

- ▼ Address electromagnetic safety in ICF schemes

Medium Term Actions <2035

Achieving a fusion plasma with the necessary parameters for energy production

- ▼ Validation of burning plasma scenarios
- ▼ Optimisation of Stellarator configurations

Maximizing overall plant efficiency by considering all influencing factors, from blanket temperature to the efficiency of the energy conversion process, the recirculated power fraction, and the lifetime of components

- ▼ Develop advanced materials (ODS steels, SiC-SiC...) and systems, taking into account temperature, durability, manufacturability and availability, for improving power plant efficiency

Including manufacturability, reliability, availability, maintainability, and inspectability (RAMI); and economic and environmental attractiveness at the early design stage

- ▲ Develop and implement waste management processes that minimise lifecycle environmental impacts and contribute to the sustainability of fusion power plants
- ▶ Develop a global maintenance strategy for fusion power plant systems (i.e. maintenance on paper) including also design for maintainability, design for inspectability
- ▲ Develop inspection technologies for as-build verification of design constraints and rapid inspection technologies in harsh fusion conditions (robots, drones...) to minimize downtime during operation
- ▶ Develop dedicated remote handling techniques as in-vessel components and pipe handling technologies for harsh fusion conditions

Managing the different levels of maturity of fusion power plant components—which will increase during the design phase—with the potential for innovation or breakthrough unknown at the start-up date (mastering an evolving design throughout its operational life)

- ▲ Develop robust and qualified simulation capabilities, including those for predicting the many complex interactions between plasma, components and engineering processes that take place within a fusion power plant (digital-twin)

Growing the industrial supply chain for fusion.

- ▲ Develop a milestone-based approach for introducing reliability and safety in the initial phase of the industrial supply chain

Applying the right safety rules to the right safety case and from the beginning of the design; fusion regulation is not yet stabilized and there is a risk to over-constrain the design space given the different nature of hazards

- ▲ Develop / optimize safety cases w.r.t. the integral design concepts

Managing the reactive power and exchange at plant level

- ▼ Develop and validate solutions to address the complex interactions within the power plant electrical system

Long Term Actions <2040

Achieving a fusion plasma with the necessary parameters for energy production

- ▼ ICF ignition validation in direct drive and optimization of implosion-ignition conditions

Achieving a continuous and stable supply of electricity to the grid

- ▼ Develop integral solutions that allow producing a continuous and stable supply of electricity to the grid, by controlling output and recirculating power or e.g. operating an energy storage system

Table 1 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology

5.3.2. Tritium Breeding Blanket and First Wall

Problem statement:

T production, Power exhaust, Neutron shielding.

DT fusion requires tritium self-sufficiency of the power plant by generating tritium via the (^6Li , n) and (^7Li , n) reactions using the neutrons released by the (D, T) reaction. This is implemented via the so-called tritium breeding blanket (BB), a component installed inside the vacuum vessel in front of the plasma of a fusion power plant. Overall, the BB has three main functions:

1. Production of the tritium consumed by the D-T reaction (self-sufficiency of the power plant)
2. Extraction of fusion energy deposited by the plasma and fusion neutrons in the form of heat via a coolant, under conditions suitable for maintaining an efficient thermodynamic cycle (power plant output), with the ultimate goal of producing electricity
3. Protection of downstream components (vacuum chamber, superconducting magnets) from fusion neutrons and secondary radiation

In addition, the structure of the BB must withstand interaction with high-energy neutrons for a sufficiently long period to maintain high component integrity and plant availability, both of which are necessary for commercial operation and for reducing radioactive waste generation. Similarly, the impact of the plasma on the surface of the BB first wall is critical for the component's lifetime.

In MCF power plants, the first wall (FW) is expected to be fully integrated with the BB due to a relatively low heat load requirement ($\sim 1 \text{ MW/m}^2$). However, during transient and off-normal events, the heat load deposited on the wall could be much greater than the steady-state heat load and exceed the FW limit. To protect the FW during such events, specific plasma-facing components (sacrificial limiters) at designated locations are required. In ICF power plants, where the first wall (FW) can be a separate component from the BB, it is subjected to X-ray and ion irradiation that may exceed the neutron load. This specificity should be considered in the development and qualification of materials.

BB concepts vary with respect to breeder materials (e.g. Li ceramics, liquid PbLi), neutron multiplier materials to compensate for neutron losses (Be or Pb or their compounds), the coolant for efficient extraction of fusion power (e.g. water, He, or liquid metals), and the structural materials (e.g. EUROFER steel).

Such components have never been manufactured nor tested in a fusion environment. The current maturity of these technologies is not sufficient to ensure the required performance for a fusion power plant. The current TRL for the complete system is still quite low and will need to rise to a high TRL to realize an entire fusion power plant. Thus, these systems must be qualified beforehand.

In the specific case of ICF, a significant portion of the available solid angle may be unavailable for tritium breeding because it is occupied by the optics

required for laser delivery. This limitation will be addressed in Gap 5.3.8: 'Targets (ICF)'.

Challenges:

- 5.3.2.1. Tritium delivery (production and release): to ensure T self-sufficiency of the plant and, potentially, provide the start-up inventory for further plants
- 5.3.2.2. Heat recovery: to enable highly efficient electricity generation
- 5.3.2.3. Reliability of operation: to avoid accidents and unplanned down-time of the plant
- 5.3.2.4. Availability: combination of component lifetime and remote maintenance/replacement efficiency
- 5.3.2.5. Structural and functional materials development and qualification
- 5.3.2.6. Supply chain for specific fusion power plant materials
- 5.3.2.7. Manufacturability by commercial techniques that allow standardization and cost & time savings
- 5.3.2.8. FW sustaining very high heat flux and particle (X-rays, ions, neutrons) irradiations

Figure 2. Tritium Breeding Blanket and First Wall — Challenges and Actions Summary



Table 2 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology

Table 2. Tritium Breeding Blanket and First Wall — Challenges and Actions

Short Term Actions <2030

Tritium delivery (production and release): to ensure T self-sufficiency of the plant and, potentially, provide the start-up inventory for further plants

- ▼ Design breeding blanket solutions taking into account concepts based on different breeders to maximize the tritium breeding ratio
- ▼ Construct facilities for testing BB assemblies (basic units and modules) under power plants -relevant conditions without neutrons (e.g., coolant loops) and with neutrons (neutron sources) to test the overall behaviour up to relevant TRL's

Heat recovery: to enable highly efficient electricity generation

- ▼ Design breeding blanket solutions taking into account different cooling concepts with improved efficiency, maintainability and reliability
- Develop additive-manufactured ferritic-martensitic steel first-wall structures with conformal cooling channels

Reliability of operation: to avoid accidents and unplanned down-time of the plant

- ▼ Develop / optimize safety cases w.r.t. the available integral BB design concepts and the related facilities

Availability: combination of component lifetime and remote maintenance/replacement efficiency

- ▲ Develop asset integrity procedures for BB (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing experiments

Supply chain for specific fusion power plant materials

- ▼ Develop / optimize & qualify efficient ⁶Li enrichment processes: identify the most feasible technique for isotope separation, attending to the scalability of the process and the environmental impact; to establish a regulatory framework to produce Li for fusion under nuclear standards (e.g. ISO); establish industrial protocols to assure an affordable ⁶Li production; produce trials according to the regulatory framework to demonstrate industrial capacity

Manufacturability by commercial techniques that allow standardization and cost & time savings

- ▲ Mock-up for blanket welding validation

Medium Term Actions <2035

Tritium delivery (production and release): to ensure T self-sufficiency of the plant and, potentially, provide the start-up inventory for further plants

- ▼ Improve & qualify BB first wall shielding materials & assemblies (W-based materials incl. optimized materials for accidental scenarios, W-EUROFER and W-advanced structural materials assemblies...) under fusion power plant neutron, ion, and gammas/X-rays irradiation, including the optimization of manufacturing processes
- ▼ Develop / optimize & qualify efficient tritium extraction processes from the BB: a) performing experiments with deuterium/tritium in dedicated facilities to compare the behaviour of the different existing technologies (i.e. permeation against vacuum, gas liquid contactors, vacuum sieve tray...); b) developing specific models that reproduce the experiments and perform the scalability of the technique; c) demonstrating the scalability (in terms of manufacturability) from lab, to fusion power plant, constructing 1:1 prototypes
- ▲ Develop components for reduction of tritium permeation and retention control (e.g. SiC/SiC layer)

Heat recovery: to enable highly efficient electricity generation

- ▲ Develop / optimise innovative breeding blanket design solutions for maximising efficiency, maintainability and reliability. Demonstrate related systems operation at high temperatures while minimizing T2 losses

Reliability of operation: to avoid accidents and unplanned down-time of the plant

- ▲ Develop simulation tools able to extrapolate neutron irradiation effects and first wall load effects between different operation conditions
- ▼ Develop components as corrosion barrier (e.g. SiC) for blanket structures to enhance coolant compatibility and reduce corrosion-driven degradation

Availability: combination of component lifetime and remote maintenance/replacement efficiency

- ▼ Develop / optimize remote maintenance operation and plant logistics concepts w.r.t. the available integral BB design concepts
- ▶ Develop ISI techniques in conjunction with defect assessment methodologies to predict lifetime and replacement of components
- ▼ Develop/optimize auxiliary systems for liquid breeders such as pumps, I&C, purification system, chemical and volume control systems.

Structural and functional materials development and qualification

- ▲ Develop C&S for advanced materials, joining techniques and unprecedented operating conditions
- ▼ Improve & qualify BB functional materials (Li-based breeder materials, neutron multipliers, anti-corrosion and anti-permeation coatings) under power plant-relevant neutron irradiation. Optimise manufacturing processes and establish industrial protocols to assure an affordable production
- ▲ Develop integrated modelling tools to complement the qualification and validation of the different BB concepts
- ▼ Corrosion testing of structural materials for construction of transport systems of BB-relevant fluids (e.g., PbLi, molten salts, etc.)

Supply chain for specific fusion power plant materials

- ▶ Secure long-term beryllium suppliers and assess recycling for irradiated components used in fusion environment
- ▶ Develop safe logistics, handling protocols and standards for radioactive or toxic materials

Manufacturability by commercial techniques that allow standardization and cost & time savings

- ▲ Develop manufacturing techniques (additive manufacturing, machining, welding, etc.) that allow producing components that meet fusion quality standards with cost savings
- ▲ Develop at industrial scale manufacturing routes for complex blanket components
- ▲ Establish standards for quality control and qualification for blanket components

FW sustaining very high heat flux and particle (X-rays, ions, neutrons) irradiations

- ▼ Address pulsed particle damage and durability of First Wall and optical materials in ICF burst-mode experiments and modelling
- ▼ Develop relevant components to protect the First Wall during transient and off normal heat and radiation loads

Long Term Actions <2040

Heat recovery: to enable highly efficient electricity generation

- ▲ Improve durability of neutron resistant structural materials (RAFM-steels, ODS-steels, SiC/SiC, or any other material compatible with advanced liquid/molten salt breeder...) under fusion power plant relevant neutron fluences and temperatures, including industrial upscaling

Availability: combination of component lifetime and remote maintenance/replacement efficiency

- ▶ Develop structural Interface Layers for Hybrid Joints (e.g. SiC) to mitigate mismatch stresses, protect against corrosion, improve lifetime of blanket/divertor assemblies

Structural and functional materials development and qualification

- ▼ Conduct experiments on BB structural materials to achieve damage levels similar to those expected in a fusion power plant (neutron sources and corresponding PIE facilities)
- ▲ Establish reliable databases of material properties with traceable, quality-screened data measured according to international standards

5.3.3. Tritium Fuel Cycle

Problem statement:

The Tritium Fuel Cycle is essential in any DT fusion approach to provide the tritium (and deuterium) fuel to the reaction chamber as required, to remove the fusion reaction products (helium and impurities) by vacuum pumping from the reaction chamber (thus allowing the continuation of the fusion reaction and recycling the unburnt fraction of the fuel), and to control plasma performance and heat loads (depending on the chosen physics concept). Furthermore, the polluted DT fuel, both from the reaction chamber and from the Tritium Breeding Blanket, must be purified for (re-) use, possibly including isotope rebalancing.

Additionally, excess tritium (e.g., produced to provide the start-up inventory for the next power plant) must be stored reversibly. As tritium is not only radioactive but can also easily replace “normal” hydrogen (e.g., in water), its incorporation is extremely hazardous. It must therefore be safely contained in a closed-loop cycle, bearing in mind that, due to its radioactivity, it will undergo reactions that normal hydrogen will not under the same conditions (e.g., producing tritiated methane from carbon contained in steel or polymers, or producing tritiated water from coolant water, purge gas dotation, or oxide layers). Moreover, for safety and licensing reasons—as well as because of inventory losses due to its natural decay—the tritium inventory in a power plant must be reduced to the minimum required to guarantee continued plant operation and, if possible, production of excess tritium for future power plants, including planned or unplanned interruptions.

This, in turn, has implications for the processes and equipment to be used, which must be optimized to achieve a low operational tritium inventory.

The TRLs of the processes involved in tritium processing need to be increased. Some currently have relatively low performance and robustness, which do not meet the requirements for an efficient fuel cycle.

The recovery of tritium from materials is an opportunity to optimize fuel use. This may concern not only tritium in plasma-facing components in operation but also tritium in radioactive waste materials. For other topics, such as fuelling injection and pumping technologies, where technologies already exist, they must be validated for tritium compatibility and fully commercialized by industry. Tritium transport modelling at the system level is essential for controlling tritium in both the inner and outer cycles and for supporting regulatory activities.

Among the activities listed so far—and, in principle, of high future importance for both MCF and ICF—there is one of particular relevance for today’s ICF activities: fuelling. It is necessary to address the high-repetition-rate operation of the future European implosion facility. Here, we consider only the insertion technology and metrology of capsules and their positioning, synchronized with the laser pulses. Capsule quality will be dealt with in the specific gap for targetry 5.3.8. Also, in the case of inertial fusion energy, a key aspect is the pulsed exhaust of gases (containing debris and tritium) from the chamber interior, which establishes the appropriate rate for these procedures.

Challenges:

- 5.3.3.1. Reaction chamber fuelling techniques (different for magnetic and inertial confinement fusion)
- 5.3.3.2. Tritium-compatible vacuum pumping
- 5.3.3.3. Hydrogen purification, isotope separation, recovery (from large gaseous streams and materials), and storage
- 5.3.3.4. Minimization of tritium release and tritium inventories across the entire process chain
- 5.3.3.5. Continuous fuel cycle operation in steady-state fusion devices
- 5.3.3.6. External tritium production, economically feasible to procure the necessary amount of tritium to start new machines

Figure 3. Tritium fuel cycle — Challenges and Actions Summary



**Table 3. Tritium fuel cycle — Challenges and Actions**

Short Term Actions <2030

Reaction chamber fuelling techniques (different for magnetic and inertial confinement fusion)

- ▼ Establish a staged approach to pellet testing and long-term stability optimization using integrated pellet testbeds
- ▲ Modelling and software developments (pellet creation, acceleration/injection, tube optimisation, pellet-plasma interaction) (MCF)
- ▼ Design, improve and qualify high frequency injection technology of DT targets, including both cryogenic and room temperature conditions, compatible with high-speed operations and supports mass target manufacturing (ICF)
- ▲ Improve systems for target metrology and, tracking in the chamber, and synchronization with laser operation (ICF)

Tritium-compatible vacuum pumping

- ▲ Improve and qualify tritium-compatible rough vacuum pumping technology
- ▶ Develop schemes for management of exhaust of gases (containing debris and tritium) from the interior of the chamber in a pulsed way, establishing the appropriate rate for those procedures (ICF)

Hydrogen purification, isotope separation, recovery (from large gaseous streams, materials) and storage

- ▼ Improve and qualify hydrogen (tritium, deuterium) purification and rebalancing technologies. Develop thermodynamic models that reproduce the H-isotope separation
- ▼ Improve and qualify techniques for tritium recovery of low/very low tritium concentrations from large gas streams
- ▼ Develop modelling software for tritium transport simulation and fuel cycle design
- ▼ Develop graded, goal-oriented EU framework and standards for tritium handling

Minimize tritium release and tritium inventories across the entire process chain

- ▲ Develop and qualify tritium permeation-barrier coatings and sealing boundaries, standardise permeation test protocols and consolidate EU database
- ▲ Process simulation and accountancy model development and validation, incl. a shared H-isotope property database and non-destructive tritium detection in solids
- ▲ Develop optimized reversible storage and transport concepts for tritium available

Continuous fuel cycle operation in steady-state fusion devices

- ▼ Demonstrate the capability of continuous tritium fuel cycle operation and control with reduced processing times
- ▼ Model architecture of fuel cycle for continuous fusion power plant, , show feasibility
- ▲ Develop/optimize safety cases w.r.t. the available integral Tritium Fuel Cycle design concept
- ▲ Develop asset integrity procedures for fuel cycle (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing experiments

Tritium external production, economically feasible to procure the necessary amount of tritium to start new machines

- ▼ Develop a strategy for tritium supply for fusion applications
- ▲ Explore tritium external production in fission reactors



Medium Term Actions <2035

Reaction chamber fuelling techniques (different for magnetic and inertial confinement fusion)

- ▲ Develop, qualify and optimize frozen DT pellet fabrication and injection technologies incl. diagnostics development (MCF)
- ▼ Assess the potential transition from cryogenic to non-cryogenic targets and its implications for the design and operational requirements of ICF target injectors

Tritium-compatible vacuum pumping

- ▼ Improve and qualify tritium-compatible primary vacuum pumping technologies incl. hydrogen selective pumps

Hydrogen purification, isotope separation, recovery (from large gaseous streams, materials) and storage

- ▲ Optimize real-time tritium detectors (room, wearable, water) for operations& safety, improve response time and sensitivity
- ▲ Develop and industrialise hydrogen-specific devices like Pd-Ag membrane modules or equilibrators catalyst beds
- ▲ Waste treatment and tritium recovery processes for PFCs, materials, water and gas exhaust
- ▼ Develop facilities for qualification of components in tritium environment

Minimize tritium release and tritium inventories across the entire process chain

- ▼ Develop and optimize fuel cycle architecture to minimize tritium inventory in the overall tritium plant e.g. by including selective pumping
- ▼ Tritium accountancy: methods, software tools, high-flow measurement accuracy

Long Term Actions <2040

Tritium-compatible vacuum pumping

- ▲ Develop pump integration schemes into the fusion power plant (MCF)

Tritium external production, economically feasible to procure the necessary amount of tritium to start new machines

- ▶ Explore accelerator-based tritium production (e.g. lithium target + proton beam) as a backup strategy analyzed

Table 3 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology

5.3.4. Diagnostic & Control

Problem statement:

An efficient Diagnostic and Control (D&C) system is crucial for the overall availability and control of a future fusion power plant and of intermediate test facilities. It must provide high reliability for the protection of machine components, high accuracy for reliable operation near operational limits and maximised power output, and rapid responses in the event of unforeseen transient events that could lead to a loss of plasma control (in the case of MCF) or implosion control (in the case of ICF). Moreover, dedicated sensors will need to be developed for various fusion power plant subsystems—such as breeding blankets, magnets, heating systems, and vacuum systems—to ensure their monitoring, control, and safe operation. In contrast to current plasma devices, where extensive diagnostic systems are used to provide the measurements necessary for control, evaluation, and optimisation of plasma performance (in the case of MCF), or target implosion and laser coupling efficiency (in the case of ICF), future fusion power plants will impose severe limitations in terms of possible diagnostic implementation. Space restrictions due to tritium breeding blankets and RAMI requirements will clearly limit the number of diagnostics. In addition, the high fluence of plasma particles and neutrons, as well as radiation loads, will impact diagnostic front-end components, affecting the quality of measurements (which may degrade over time) or even preventing the use of currently available measurement methods. For reliable operation and safety, diagnostics must have very high availability and ensure reliable, high-

quality data acquisition. Furthermore, they must meet stringent engineering requirements for tritium confinement, vacuum integrity, neutron shielding, and remote-handling maintainability.

These limitations will also apply to ICF fusion power plants, but for an intermediate implosion facility, they will be less significant. Achieving the best conditions for direct-drive implosion will mandatorily require the use of a large number of diagnostics and the development of tailored diagnostic methodologies and devices for laser-matter interaction and implosion quality.

Today's diagnostic systems have never been used in a high-fluence nuclear environment. Their technological maturity in a power plant environment is low, regardless of where they are implemented. However, neutron yields in excess of 10^{18} neutrons were created on NIF during ignition experiments, and in the highest JET performance in DT operations 2.46×10^{19} neutrons were produced over about 6 s with a neutron yield rate peak of 5.06×10^{18} n/s (record pulse #104522). In both cases, mitigation strategies were implemented (e.g., hardened fiber-optic cables). These conditions, however, are still very far from those expected in fusion power plants. The establishment of a dedicated radiation testing program for diagnostic components at fission reactors, in combination with fusion neutron, X-ray/gamma, and ion sources, is mandatory for the successful deployment of the fusion power plant control system.

Challenges:

- 5.3.4.1. Overall plant diagnostic architecture providing all necessary information for operation and control systems, taking into account fusion power plant-specific constraints, including steady-state operations.
- 5.3.4.2. In-vessel components with a high degree of reliability and durability, to ensure high overall plant availability. The typical lifetime of in-vessel diagnostic and control components should be well above the mean time between planned blanket replacements.
- 5.3.4.3. Advanced/intelligent control and data management techniques are required to optimize controllability, given the limitations of available diagnostics and actuators.
- 5.3.4.4. Instrumentation for control systems
- 5.3.4.5. Diagnostics to monitor and control interaction conditions and target-to-plasma/target-to-debris conversion processes, increase the gain to levels suitable for energy production, and support the achievement of ignition

Figure 4. Diagnostic & Control — Challenges and Actions Summary

Table 4. Diagnostic & Control — Challenges and Actions

Short Term Actions <2030

Overall plant diagnostic architecture providing all necessary information for operation and control systems, taking into account fusion power plant-specific constraints, including steady-state operations

- ▼ Develop to steady state operation the plasma control strategy based on an integrated architecture including plasma actuators and relevant plant subsystems
- ▼ Development of simulation tools and non-deterministic approaches for management of plasma instabilities for steady state operations.

In-vessel components with a high degree of reliability and durability, to ensure high overall plant availability. The typical lifetime of in-vessel diagnostic and control components should be well above the mean time between planned blanket replacements

- ▲ Development and qualification of materials for diagnostics

Advanced/intelligent control and data management techniques are required to optimize controllability, given the limitations of available diagnostics and actuators

- ▼ Develop asset integrity procedures for diagnostics based on experimental and industrial experiences and develop database using data of failures of the existing experiments

Instrumentations for control systems.

- ▲ Develop functional and architectural models for High speed interlock systems

Medium Term Actions <2035

Overall plant diagnostic architecture providing all necessary information for operation and control systems, taking into account fusion power plant-specific constraints, including steady-state operations

- ▼ Compile the minimum necessary control functions and the corresponding control strategies for the respective fusion power plant approach, despite current uncertainties about the physics basis.
- ▼ Develop effective control methods and technologies to minimize the impact of Loss of Off-site Power (LOOP) events on machine operation and ensure safety

In-vessel components with a high degree of reliability and durability, to ensure high overall plant availability. The typical lifetime of in-vessel diagnostic and control components should be well above the mean time between planned blanket replacements

- ▲ Select required diagnostic methods with regards to their robustness in view of durable and reliable measurements for plasma control and performance, retracting vulnerable front-end components into protected areas.
- ▲ Develop and test diagnostics for reliable plasma equilibrium control and reliable plasma performance measurements, with sensors providing signal long-term stability under relevant neutron irradiation (e.g. magnetics, neutron & gamma meas.).
- ▶ Bring wall conditioning techniques to maturity for power plant first plasma start-up or post-replacement start-up (control oxygen, water and other impurities by GDC, boronization)

Advanced/intelligent control and data management techniques are required to optimize controllability, given the limitations of available diagnostics and actuators

- ▲ Develop and test advanced control modules taking into account the detailed properties of the plasma scenario and of the machine, as well as sensors and actuator properties.
- ▼ Develop model-predictive plasma control algorithms integrated with a digital twin and IA applications to diagnostics and control systems algorithms integrated with a digital twin and IA

applications to diagnostics and control systems

Instrumentations for control systems.

- ▲ Select the required diagnostic/sensors for special systems (using tritium, liquid metals, molten salts, etc.) and develop the missing ones.

Diagnostics to monitor and control interaction conditions and target-to-plasma/target-to-debris conversion processes and increase the supporting the achievement of ignition

- ▼ Develop and test laser-plasma instabilities and laser coupling diagnostics to control interaction conditions and target-to plasma / target -to-debris conversion processes
- ▲ Development of laser beam synchronization and steering to injected target, including target tracking system and metrology.
- ▼ Real time diagnostics operating at high repetition rates.
- ▲ Develop and test ultra-short radiation sources (ion, x-ray, neutron) for laser plasma diagnostics and material assessment.
- ▼ Develop diagnostics systems and electronics capable to withstand the huge Electromagnetic Pulses (EMP) which will be generated when the lasers fire on target.
- ▶ Develop and test diagnostics for implosion and high gain physics.

Long Term Actions <2040

In-vessel components with a high degree of reliability and durability, to ensure high overall plant availability. The typical lifetime of in-vessel diagnostic and control components should be well above the mean time between planned blanket replacements

- ▲ Development of techniques to replace diagnostics without turning off the machine.

Advanced/intelligent control and data management techniques are required to optimize controllability, given the limitations of available diagnostics and actuators

- ▶ Develop and test event-driven processes to manage off-normal events, including event driven data buffering and data storage.
- ▶ Develop real time 3-D magnetic field reconstruction diagnostics for stellarators using sparse sensors arrays & ML-assisted inversion.
- ▲ Assess the need of hypervisors as a mean of increasing software safety and security of the safety critical applications in embedded environments

Table 4 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology

5.3.5. Magnets and Cryogenics (MCF)

Problem statement:

Provide the high magnetic fields required for magnetic confinement fusion at the lowest possible capital and operating costs.

Low-temperature superconducting (LTS) technologies have been known and used for several decades to generate strong magnetic fields. Their use is currently limited to large physics instruments (CERN's high-energy accelerators and particle detectors, magnetic confinement fusion tokamaks or stellarators), and magnetic resonance systems for medical applications.

The high cost of today's superconducting systems—such as those to be used in ITER—as well as the investment and operating costs of the associated infrastructure, particularly cryogenic infrastructure for operation at very low temperatures (helium at 2.8 K), have been identified as potential obstacles to wider industrial deployment. In a fusion power plant, magnets and cryogenic systems account for about 30% of the capital cost.

Recent advances in the field of high-temperature superconductors (HTS) open new opportunities, particularly through a more favourable cryogenic environment (at 10–20 K or higher), access to higher magnetic fields (>20 T), and reduced sensitivity to external disturbances. However, the TRL of such techniques remains low.

At the same time, the development and testing of demountable coils and flexible schemes for superconducting magnets

may significantly simplify manufacturing and construction and improve maintenance operations—leading to substantial gains in plant availability.

Many areas of development in superconducting materials and magnets rely on highly relevant technologies applicable to various fields and markets outside fusion energy development.

Challenges:

- 5.3.5.1. Enhancing operating margins compared to LTS
 - 5.3.5.2. Reducing manufacturing and operating costs compared to LTS
 - 5.3.5.3. Developing quench detection and protection for HTS
 - 5.3.5.4. Developing remote maintenance schemes and magnet technology
 - 5.3.5.5. Advanced instrumentation and cryogenics for magnets
 - 5.3.5.6. Developing an integrated validation program for fusion power plant HTS magnets
 - 5.3.5.7. Improving the radiation resistance of LTS and HTS coils
-

Figure 5. Magnets and Cryogenics (MCF) — Challenges and Actions Summary



Table 5. Magnets and Cryogenics (MCF) — Challenges and Actions

Short Term Actions <2030

Enhancing operating margins compared to LTS

- ▲ Develop and test innovative superconducting materials (HTS) for advanced conductors and magnets.
- ▼ Develop and qualify HTS high current multi-tape conductors, including cooling scheme, that can reach several tens of thousands of amperes.
- ▼ Manufacturing and test of large-scale HTS model coil

Reducing manufacturing and operating cost compared to LTS

- ▼ Industrial scale-up of HTS (REBCO) tapes production

Developing quench detection and protection for HTS

- ▲ Develop active (e.g. current limiting devices, bypass systems) and passive systems (e.g. quench heaters) for quench protection.
- ▲ Develop a predictive HTS cooling model for anticipating quench protection.
- ▼ Develop advanced non-voltage magnetic safety systems for quench detection .

Developing remote maintenance scheme and magnet technology

- ▼ Develop and test of dismountable joints for superconducting magnets to enhance remote maintenance and innovative assembly schemes

Advanced Instrumentation and cryogenics for magnets

- ▼ Increase the efficiency of HTS magnet power systems
- ▼ Develop asset integrity instruments and procedures for diagnostics (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing experiments

Developing integrated validation programme for fusion power plant HTS magnets

- ▼ Develop mockups (cable, windings, double pancake, model coils, etc.) for validating the HTS magnets technology
- ▲ Develop the conceptual design of a cryoplat capable of cooling down the magnetic system of a HTS-based fusion power plant

Improving of the radiation resistance of LTS and HTS coils

- ▼ Assess under fusion relevant conditions radiation tolerance and dose limits for HTS materials and insulators

Medium Term Actions <2035

Developing remote maintenance scheme and magnet technology

- ▲ Develop and test flexible schemes for superconducting magnets to simplify manufacturing/ construction (in situ winding, modularity, insulation approach, ...)
- ▼ Develop remote maintenance operation and plant logistics concepts w.r.t. the available magnet concept

Advanced Instrumentation and cryogenics for magnets

- ▲ Demonstrate gas-cooled cryogenic system for LTS and HTS coils to halve cryoplat power
- ▲ Alternative cryogenics based on hydrogen or cryogen-free system, to reduce the use of limited resource of helium
- ▲ High power transmission lines (Superconducting links) for energizing high field magnets (forecasted with hundreds or thousand of amperes) and associated cryogenics solutions

Table 5 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology

5.3.6. Plasma Power and Particle Exhaust (MCF)

Problem statement:

Managing and exhausting the unprecedented thermal loads generated by fusion reactions and deposited in the plasma, without damaging the power plant components or adversely affecting the quality of the burning plasma.

The long-term challenge is to provide viable solutions for power exhaust in power plant-class devices operating in high neutron flux environments. Designing novel divertor concepts is directly related to divertor magnetic configurations and power exhaust scenarios, depending on the physics boundary conditions. The development of significantly more robust and efficient heat and particle exhaust systems is mandatory. These systems must be capable of handling extreme thermal loads and particle fluxes, efficiently removing helium ash and impurities, and withstanding high

neutron fluxes while maintaining the structural integrity of the power plant and ensuring safety, availability, reliability, and maintainability.

The technological maturity level is medium for ITER-grade components, including the CuCrZr heat sink pipe and W monoblocks. However, the ITER target technology is prone to cracking at high cyclic loads due to low-cycle fatigue (crack initiation) and brittle behavior during cool-down. Copper alloys will be the only applicable option to cope with slow transient loads (up to $\sim 20 \text{ MW/m}^2$), whereas steel as a heat sink material is limited to a more modest heat flux, even with a thin pipe thickness. However, copper alloys should be operated below 300°C to provide sufficient mechanical strength. Therefore, such technology using a low-temperature coolant is not relevant for an efficient fusion power plant. Other concepts, such as those based on liquid metals, have a low TRL.

Challenges:

- 5.3.6.1. Developing suitable configurations to maximize power and particle exhaust, addressing plasma-wall interactions (first wall and divertor) in an integrated manner, and implementing the testing program
- 5.3.6.2. Developing and qualifying structural and functional materials capable of withstanding very high heat fluxes and neutron fluences without compromising their physical and structural integrity
- 5.3.6.3. Developing manufacturing techniques and industrial upscaling processes capable of ensuring the required system functions under power plant operating conditions, including additive manufacturing
- 5.3.6.4. Achieving plant availability by addressing the combination of component lifetime and remote maintenance/replacement efficiency

Figure 6. Plasma Power and Particle Exhaust (MCF) — Challenges and Actions Summary



Table 6. Plasma Power and Particle Exhaust (MCF) — Challenges and Actions

Medium Term Actions <2035

Developing suitable configurations to maximize power and particle exhaust, addressing plasma-wall interactions (first wall and divertor) in an integrated manner, and implementing the testing program

- ▼ Implementing novel divertor designs to enhance the distribution of the heat flux, thus reducing peak loads on any specific part of the power plant and to allow enhanced particle exhaust
- ▼ Implementing novel divertor designs to ensure wall protection without significant impact on TBR, maintainability, availability & cost. (incl. liquid metal-based limiter), minimise rad-waste disposal and simplify refurbishment of sacrificial targets
- ▲ Developing an integrated virtual design platform to couple multiphysics engineering simulations with power/particle exhaust physics analyses aiming at a physics-informed rational design scheme
- ▲ Design & test modular pumped divertor with liquid SnLi plasma facing surface for $\geq 20 \text{ MW m}^{-2}$ heat flux
- ▼ Develop test facilities and perform divertor testing and qualification in power plant relevant conditions

Developing and qualifying structural and functional materials capable of withstanding very high heat fluxes and neutron fluences without compromising their physical and structural integrity

- ▲ Improving neutron resistance of divertor materials and components under fusion power plant relevant neutron irradiation (e.g. IFMIF-DONES)
- ▲ Development and qualification of advanced materials having high thermal conductivity (e.g. K-doped W, W-Cu composites and ODS-Cu) capable of withstanding high heat fluxes and neutron loads, including materials that can self-repair damage due to neutron irradiation, and those based on liquid metals
- ▲ Establish reliable databases of material properties with traceable, quality-screened data (including neutron-irradiation/post-irradiation test data) measured according to international standards, and develop C&S for advanced materials, joining techniques in unprecedented operating conditions
- ▶ Develop structural integrity assessment methodologies in conjunction with HHF design-by-experiment testing

Developing manufacturing techniques and industrial upscaling processes capable of ensuring the required system functions in the power plants operating conditions, including additive manufacturing

- ▲ Implementing advanced and optimized joining techniques for the chosen materials, focusing on achieving high-quality, durable joints capable of withstanding the operational conditions
- ▲ Implementing advanced manufacturing technologies for pressurised or structural steel components with complex geometry (e.g. cassette body, supports) focusing on achieving high-quality and up-scaling to full-scale prototype dimensions
- ▲ Implementing advanced non-destructive test (NDT) techniques and data evaluation methodology for inspection to detect defects/cracks and residual stress in as-manufactured prototype components

Long Term Actions <2040

Developing and qualifying structural and functional materials capable of withstanding very high heat fluxes and neutron fluences without compromising their physical and structural integrity

- ▼ Qualifying the baseline HHF technology (ITER-like W monoblock type targets) by means of neutron-irradiation/post-irradiation HHF test & in-situ tokamak plasma exposure test (leading edge loads)

Achieving plant availability by addressing the combination of component lifetime and remote maintenance/replacement efficiency

- ▲ Implementing optimal design and conditions for ramp-up and ramp-down phases, thus, to reduce peak heat and impurity particle flux production in this phase
- ▲ Implementing "marker" layers in PFC components at critical locations for transient or steady-state erosion to identify passively (spectroscopy) or actively (laser-techniques) if repair/replacement action is required
- ▲ Bring in-situ repair/recovery techniques for most critical PFCs to maturity (laser-repair or plasma-spraying)
- ▲ Develop ISI techniques in conjunction with defect assessment methodologies to predict lifetime and replacement of components

Table 6 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology



5.3.7. Plasma Heating Systems (MCF)

Problem statement:

Provide industrialized, efficient, and reliable plasma heating systems for steady-state operation.

The basic functions of heating systems are to control the plasma's core temperature and, for tokamaks, to generate current (to extend the duration of discharges), as well as to stabilize the plasma in certain advanced scenarios. Heating efficiency (generally near the plasma core) and current generation capacity differ depending on the heating system considered, as does their overall "wall-plug" efficiency.

To date, fusion devices like ITER use various methods to heat the plasma, each with its own set of challenges and benefits. Alongside Ion Cyclotron (IC) Heating, Lower Hybrid (LHCD) heating, and Neutral Beam Injection (NBI), Electron Cyclotron (EC) Heating emerges as the best compromise for meeting the very high-performance requirements across all plasma phases (plasma breakdown, start-up, plateau, and termination phases, with control of a number of potential instabilities). This underlines the importance of validating the development of burning plasma scenarios where electron heating predominates, primarily driven by EC heating (one of the ITER missions).

Electron Cyclotron Resonance Heating (ECRH) presents a range of technical, industrial, and operational challenges. Additionally, the complexity of integrating large ECRH systems (with more than 10 gyrotrons) demands flexible, robust integration strategies. As fusion projects

scale up, addressing these challenges becomes essential.

A complete ECRH solution includes gyrotrons, transmission lines, high-voltage power supplies, cooling systems, and control and command systems. Coordinated development and integration of these subsystems is vital to ensure operational reliability and ease of maintenance. Delivering a fully integrated ECRH system will be required to reduce complexity and accelerate implementation timelines—key factors for large-scale fusion initiatives.

While ECRH continues to gain prominence, Ion Cyclotron Resonance Heating (ICRH) and NBI remain vital technologies for plasma heating in intermediate-step devices before a power plant. Preserving industrial and scientific expertise in these technologies is important, especially as they will be required in future fusion devices alongside ECRH to support a broad range of fusion applications.

The NBI system is widely used in current and upcoming experiments and offers unique features compared to other heating systems. The development of reliable, high-efficiency systems is of great interest for other devices proposed within the framework of private initiatives and for volumetric neutron sources.

Many areas of development rely on highly relevant technologies applicable to various fields and markets beyond fusion energy research. These include, on the mechanical side, the use of advanced materials and advanced manufacturing processes (such as

additive manufacturing) for both large and very high-precision components. On the electrical side, the development of high-voltage DC and AC power supplies, as well as high-voltage technologies for energy transmission lines, is essential. The integration of auxiliary plant systems, remote handling systems, and the development of automatic process control strategies using advanced

“intelligent” tools should also not be overlooked. Many of these developments will also benefit other areas of fusion power plant development.

Finally, the technological maturity of high-power, steady-state heating systems has yet to be demonstrated for use in a fusion power plant (low TRL).

Challenges:

- 5.3.7.1. Industrialization and adaptation to power plants of today's heating systems, including steady-state operation requirements.
- 5.3.7.2. Operational efficiency of today's heating systems in terms of wall-plug efficiency
- 5.3.7.3. Reliability, availability and lifetime of today's heating systems
- 5.3.7.4. Nuclear compatibility of RF launcher components/concepts

Figure 7. Plasma Heating Systems (MCF) — Challenges and Actions Summary



Table 7. Plasma Heating Systems (MCF) — Challenges and Actions

Short Term Actions <2030

Industrialization and adaptation to power plants of today's heating systems, including steady-state operation requirements

- ▲ Develop and design high frequency (170 – 300 GHz), multifrequency, high power (1 to 2 MW), lower TCO, steady state gyrotrons with high efficiency (> 50%), manufacturability and reliability
- ▲ Develop industrial test benches for gyrotrons qualification and conditioning
- ▼ Develop complete ECRH system integrating all components
- ▼ Develop fast installation mechanisms, intelligent control and adjustment systems to reduce installation time and operate gyrotrons at optimum operating points
- ▼ Increase the production capacity of gyrotrons
- ▼ Maintain expertise, know-how & industrial capability on ECRH & ICRH
- ▼ Develop high efficiency and compact Power Supplies for Gyrotrons (MHVPS; BPS; APS)
- ▼ Develop Additive Manufacturing of high precision mechanical components

Operational efficiency of today's heating systems in terms of wall-plug efficiency

- ▲ Develop ECRH transmission line technology for output power levels > 1MW

Nuclear compatibility of RF launcher components/concepts

- ▼ Development of optimal control strategy of RF plasma heating (ICRH, ECRH, EBW, LHH) to sustain heating plasma and steady state operation

Medium Term Actions <2035

Operational efficiency of today's heating systems in terms of wall-plug efficiency

- ▼ Develop ICRH power sources of high efficiency, in the frequency range 40-120 MHz, targeting 2 to 3 MW, possibly based on solid state technology

Nuclear compatibility of RF launcher components/concepts

- ▲ Develop and test steady-state, high-heat-flux, radiation resistant and maintainable IC and EC RF launcher components, targeting a power per launcher of 30 to 50 MW, including appropriate steering mechanism (mechanical steering, remote steering and frequency steering) resistant to high neutron flux

Long Term Actions <2040

Operational efficiency of today's heating systems in terms of wall-plug efficiency

- ▲ Develop high efficiency (>50%) neutral beam injectors (neutralization system, pumping systems, RF ion sources), possibly via alternative concepts

Reliability, availability and lifetime of today's heating systems

- ▼ Explore quasi-optical transmission technology

Nuclear compatibility of RF launcher components/concepts

- ▶ Develop and test functional materials for power windows and mirrors application in a representative power plant environment, including advanced diamond windows and window assemblies with lower losses for higher output power and for broadband operation respectively

Table 7 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology

5.3.8. Targets (ICF)

Problem statement:

One of the critical factors enabling the recent remarkable NIF results is the extremely high quality of the capsule. NIF's experiments are conducted in indirect-drive mode, which presents significant challenges for future ICF power plants. For this reason, current mainstream research in Europe explores direct-drive approaches. Target characteristics will differ from those of indirect drive, but capsule quality will remain of primary importance. A future ICF power plant will require mass-target fabrication, high-target quality, metrology, target injection, and target positioning. Target fabrication is under continuous development due to increasing demand from other high-energy-density physics experiments at X-ray radiation facilities such as ELL, EuXFEL, and ESRF. The requirements for ICF target quality, cost, and materials are compatible with technologies already developed in industry. Recent achievements in micro-lithography and the mass production of microchips share many technological requirements with ICF, providing a solid reference for future ICF technologies. Mass production can significantly reduce target costs.

The use of low-density material (foam) shells impregnated with liquid DT is a possible alternative to solid DT shells, even if contamination of the DT by the structuring foam results in reduced plasma reactivity. Additionally, foams

are considered potential ablaters in target design (improving laser-plasma coupling and shock generation) and an effective tool for mitigating laser imprint and hydrodynamic instabilities.

It is also important to evaluate the possible shift towards non-cryogenic targets. This would make target supply and injection easier, especially in high-repetition-rate regimes.

A potentially critical aspect is target survivability. The targets will be injected into a gas/vapour atmosphere, with a density to be clearly defined, which will critically affect the final performance of high-gain cryogenic targets.

For ICF, it is also important to assess the possibility of using lithium-doped targets to produce tritium during the interaction. These studies require an implosion facility, but preliminary investigations can be undertaken in existing European laser facilities.

Finally, the complex and extremely strategic issue of targetry and effective laser-target coupling requires the development of suitable numerical codes capable of describing the different physics involved in the processes of laser-matter interaction and target implosion, as well as a robust assessment of advanced target concepts based on novel materials such as nano- or micro-structured materials (foam).

Challenges:

- 5.3.8.1. Develop requirements for advanced direct drive schemes and develop robust, high-efficiency and low-cost targets.
 - 5.3.8.2. Assess feasibility of using solid-state non-cryogenic targets.
 - 5.3.8.3. Develop requirements for target quality, cost and materials.
 - 5.3.8.4. Assess and improve material properties to address ICF requirements
-

Figure 8. Targets (ICF) — Challenges and Actions Summary



Table 8. Targets (ICF) — Challenges and Actions

Short Term Actions <2030

Develop requirements for target quality, cost and materials

- ▼ Assessment of micro-structured materials (foams) impregnated with liquid DT, as alternative to solid DT
- ▼ Assessment of nano- and micro-structured materials (foams) as advanced ablators in the target design to improve laser-plasma coupling and for mitigation of laser imprint and hydrodynamic instabilities

Assess and improve material properties to address ICF requirements

- ▼ Assessment and optimization of material properties to address ICF requirements. Application of additive manufacturing techniques

Medium Term Actions <2035

Develop requirements for advanced direct drive schemes and develop robust, high-efficiency and low-cost targets

- ▼ Assessment of target characteristics in advanced Direct-Drive schemes
- ▼ Design and test high-gain targets compatible with high-speed operation (10 Hz) with optimized architecture (density gradients between materials) / implosion speed / cold fuel entropy and compression levels/laser temporal waveform
- ▼ Develop and validate robust simulation codes to predict target performance, emitted particles, radiation spectra and debris emission
- ▼ Design and test facilities and structures for a European DD-ICF implosion facility that minimize required coolant flow, generate required T2, withstand the produced pressures, and achieve the required repetition rate, for application to an ICF power plant design
- ▲ Address the management of burst-mode operation, including control of interaction conditions and target-to-plasma/target-to-debris conversion processes in DD-ICF

Develop requirements for target quality, cost and materials

- ▲ Assessment of requirements for target quality, cost and materials, in relation with technologies developed in the industry, for an implosion facility, with prospective view for a power plant

Long Term Actions <2040

Assess feasibility of using solid-state non-cryogenic targets

- ▶ Assessment of solid-state non-cryogenic targets including low-tritium content targets and self-breeding targets for ICF (containing lithium)

Table 8 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ▶ Promotes EU strategic autonomy in fusion science and technology

5.3.9. High Performance Lasers (ICF)

Problem statement:

The development of laser systems that ensure both a positive overall energy yield and the most efficient possible coupling to the target is a key requirement for a future ICF power plant. The NIF (and the LMJ in France) lasers have been designed and implemented for an indirect-incidence scheme using an intermediary gold cavity. Consequently, the geometric arrangement of the laser beams around the chamber is optimized for cavity experiments, with the beams grouped into two (LMJ) or four (NIF) cones around the target's vertical axis of symmetry. Laser beams will always be absent from the equatorial plane of the target. This arrangement provides increased implosion stability but low energy efficiency. In contrast, a direct incidence scheme—in which the laser beams are focused directly on the target to be imploded—offers greater energy efficiency but is more sensitive to instabilities during the early stages of the implosion.

The direct-drive scheme requires a new generation of laser sources with more stringent beam-quality specifications. According to the scientific community, this scheme is necessary to achieve high target yields at a controlled unit target cost. Beyond the irradiation scheme, laser source parameters play a key role. For example, choosing harmonics closer to the fundamental ($1.054\ \mu\text{m}$, in the case of neodymium-doped glass), instead of the classical third harmonic used today for implosion, will increase the laser source efficiency and the optics damage threshold, but degrade the coupling to the target.

To minimize the non-linear mechanisms that degrade this coupling, breaking the space-time coherence of laser sources might be beneficial, leading to sources with a wide spectral bandwidth. Finally, high-rate operation requires controlling thermal issues in the laser chain, and high energy efficiency means that the laser efficiency “at the plug” must be a few tens of percent (compared to a fraction of a percent in the NIF or LMJ flash-pumped systems to date). The technological demonstration of such a laser source—combining large bandwidth and robust operation at approximately 10 Hz—remains to be achieved. Diode-pumped laser modules operating at 10 Hz and delivering nanosecond-duration, about 100 J laser pulses are already available on the market but must ultimately be scaled in both bandwidth and energy towards $>1\ \text{kJ}$ per beamline. Although the intrinsic modularity of the lasers is an asset for an implosion facility or future power plant requirements, many significant technological steps remain to be taken.

Challenges:

- 5.3.9.1. High-performance megajoule-class lasers with efficient coupling to the target for direct-drive implosion facilities
 - 5.3.9.2. Modular structure of the full-scale laser
 - 5.3.9.3. Laser design for high wall-plug efficiency, high repetition rate, and low maintenance cost to achieve ICF power plant performance
 - 5.3.9.4. Beam transport and optics
-

Figure 9. High Performance Lasers (ICF) — Challenges and Actions Summary





Table 9. High Performance Lasers (ICF) — Challenges and Actions

Short Term Actions <2030

High-performance megajoule-class lasers with efficient coupling to the target for direct-drive implosion facilities

- ▼ Identify and examine functional modular laser blocks in terms of parameters required for operation in burst mode and at 10 Hz
- ▼ Assess the current status, availability, limits (performance, TRL, cost, reliability) of required diode-laser pump technology, develop and test advanced diode-pumped laser modules and systems, and establish the roadmap enabling scalable industrial diode-laser pump technology.
- ▼ Develop schemes for effective dynamical modification of laser focusing during direct-drive compression
- ▲ Identify and assess solutions for increasing wall-plug efficiencies above 10%
- ▼ Definition of a design of the laser system for a direct-drive implosion facility operating in burst mode, with identification of key factors for repetition rate operation up to an intermediate pulse energy level to address power plant level issues

Modular structure of the full-scale laser

- ▼ Definition of specifications for the parameters of the main staged laser, and of the interconnections between the modular sub-stages

Laser design for high wall-plug efficiency, high repetition rate, and low maintenance cost to achieve ICF power plant performance

- ▶ Definition of a risk management process for critical components, including performance and cost scaling of diode laser pump supply, large optics and gain material



Medium Term Actions <2035

High-performance megajoule-class lasers with efficient coupling to the target for direct-drive implosion facilities

- ▼ Develop larger bandwidth laser and beam-shaping technologies to enhance laser-plasma coupling and ensure highly uniform energy delivery to the target

Beam transport and optics

- ▼ Definition of requirements and solutions for beam and final optic protection from vapor, debris and radiation
- ▼ Definition of requirements and solutions for operation of beam transport and optics with vibration protection, over long periods and without substitution



Long Term Actions <2040

Modular structure of the full-scale laser

- ▲ Develop alternative laser approaches towards MJ energies on target and schemes for synchronization of high-power laser systems (broadband, short-pulsed) on target

Laser design for high wall-plug efficiency, high repetition rate, and low maintenance cost to achieve ICF power plant performance

- ▶ Identification of solutions to scaling limitations of the laser system defined for the burst mode implosion facility to be in line with a proposed power plant level capable laser design

Beam transport and optics

- ▲ Develop methodologies and systems for stable, accurate and long-term operation of laser beam steering at MJ levels in burst mode

Table 9 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology



5.3.10. Training & Knowledge Management

Problem statement:

Train Human Resources, Operations, Maintenance, Standards.

The manufacturing of fusion-specific components is currently carried out in small quantities, which means there is a limited number of people with the required skills and know-how. This expertise must be maintained over long periods (decades), and the number of such trained individuals in Europe should increase to meet the growing demand for fusion-related components.

Another important topic is the operation of fusion devices, systems, and their components, which is so far mostly handled in and by research laboratories, with relatively limited participation from industry. Industrial partners should become increasingly involved in the specification, design, and operation of "research" fusion devices to develop the skills and resources necessary for a private operator to manufacture, integrate, and operate a Fusion Power Plant and its main systems. Similarly, maintenance of fusion devices should also be transferred to industry, and industrial maintenance and knowledge management methods should be applied within the fusion technology domain.

Enabling industrial partners to participate in the early design phases of fusion systems is essential to facilitate effective technology transfer. This collaborative approach helps bridge the gap between research and deployment, ensuring that innovations are not only technically sound but also manufacturable, scalable, and ready for integration into

future energy infrastructures.

New fusion technology-related standards may also be needed to facilitate the integration of components and systems from various manufacturers and to enhance operators' capacity to manage technology and knowledge effectively.

Beyond component-level expertise, industrial actors play a key role in developing fully integrated systems that combine multiple sub-systems. This system-level capability is crucial for reducing complexity during installation and operation, improving reliability, and accelerating deployment timelines. Integrated solutions also support standardisation and modularity, which are vital for scaling fusion technologies across diverse platforms and use cases.

Maintaining industrial know-how is critical to sustaining momentum in fusion technology development. The specialised skills required to design, manufacture, and qualify high-performance components must be preserved and continuously nurtured. Long-term investment in workforce development, training, and collaborative R&D ensures that industrial partners remain capable of supporting future fusion programmes and evolving alongside scientific advancements.

Finally, it is important to stress that industry alone will not achieve fusion: industry innovation cannot arise without a state-of-the-art, fundamental research programme that will open new pathways to fusion, support training of the fusion workforce, and drive equipment procurement.

Challenges:

- 5.3.10.1. Develop continuous education and training programs related to the various fusion technologies (including nuclear safety) and fusion device operation. Connect academia, industry, and research laboratories for such training programs.
 - 5.3.10.2. Create job opportunities for fusion-skilled talent in the private sector, attract new talent from various disciplines, and promote long-term career development.
 - 5.3.10.3. Involve industry partners in fusion device design, manufacturing, integration, operation, and maintenance via research laboratories: to transfer laboratory know-how and develop industrial methods in this domain.
 - 5.3.10.4. Maintain state-of-the-art research infrastructures and establish testing facilities (fusion devices, material test platforms, etc.), associating them with training programs and promoting knowledge transfer to industry. Involve industrial partners from the early design phases of fusion systems to facilitate effective technology transfer.
-

Figure 10. Training & Knowledge Management — Challenges and Actions Summary



Table 10. Training & Knowledge Management — Challenges and Actions

Short Term Actions <2030

Develop continuous education and training programs related to the various fusion technologies (including nuclear safety) and fusion device operation. Connect academia, industry, and research laboratories for such training programs

- ▲ Development of internship programs where students can work on industry projects through partnerships between public and private companies
- ▶ Increase fusion-related content in the University studies
- ◀ Coordinate with European fusion education and training entities that have already established links between academia, research centres and industry; i.e., FuseNet, EUROfusion.
- ▼ Maintain and develop a fully European, international master programme entirely dedicated to fusion as a supplier of engineers and master and PhD students for public and private R&D. This programme should become a hub for fusion teaching at the master level.
- ▲ Set up a programme in charge of matchmaking between fusion education programmes at the master level and private/public entities which propose jobs, internships, theses or placements. This programme should also have scholarships for the students

Create job opportunities for fusion-skilled talent in the private sector, attract new talent from various disciplines, and promote long-term career development

- ◀ Work on legal framework to ease temporary missions of skilled public officers to the industry
- ▶ Establish European Fusion Technology Academy with industry placements on HTS<S magnets, materials, tritium tech & robotics
- ▶ Create rotational fellowship programme between fusion companies, public research, and technology institutes in fusion & suppliers for cross-training engineers and scientists.
- ◀ Develop and/or sponsor activities focusing on new talent attraction at a local and European level; i.e., student competitions, job fairs, recruitment events. Training and upskilling programmes for workers including accessibility to fusion machines

Involve industrial partners from the early design phases of fusion systems to facilitate effective technology transfer

- ▲ Fund contracts in which industry will operate and maintain experimental fusion devices in the research labs

Maintain state-of-the-art research infrastructures and establish testing facilities (fusion devices, material test platforms, etc.), associating them with training programs and promoting knowledge transfer to industry

- ▲ Maintain funding of state-of-the-art research infrastructures in the public labs and increase their links to the training program and to the industry
- ▼ Develop education and training platforms for knowledge transfer and workforce training

Table 10 - Legend:

Actions priority with respect to the goal of fusion energy commercialization, categorized into four levels:

- ▼ Indispensable for deploying fusion energy
- ▲ Would accelerate fusion energy deployment
- ▶ Would increase fusion power plant design space without acceleration
- ◀ Promotes EU strategic autonomy in fusion science and technology

5.4. Project-Oriented Approach Aligned with Gap Analysis

The gap analysis presented in Section 5.3 adopts a project-oriented approach to fusion energy development. The majority of actions identified across the different gaps and challenges are inherently project oriented. Both elements—the gap analysis and the project-oriented actions—will serve as cornerstones for implementing the EU's fusion energy strategy.

From this analysis, several testing / enabling facilities and two high-level integrated infrastructures have emerged within the SRIA:

- **Testing/Enabling Facilities for R&D of Critical Technologies:** These facilities will focus on advancing research and development of crucial technologies essential for fusion energy. By providing state-of-the-art testing environments, they will facilitate innovation and accelerate technological breakthroughs.
- **Fusion Pilot Plant (MCF):** The pilot plant is pivotal in demonstrating the viability of magnetic confinement fusion as a reliable and scalable energy source. It is instrumental in transitioning from prototyping phases to commercialization and will enable a first-of-a-kind (FOAK) fusion power plant.
- **Inertial Implosion Facility (ICF):** This facility will integrate ICF science and technology to investigate the potential of inertial direct-drive confinement as a future energy source. It will deliver key insights into direct-drive schemes—such as central hot-spot ignition, shock ignition, and fast ignition—toward potential ICF pilot plants.

The challenges and actions identified in the SRIA are aligned with the goals and implementation activities for each project. A summary of these elements is shown in Table 11.

As a dynamic document, the SRIA will be continuously updated to reflect ongoing advancements in the EU fusion landscape. This adaptability ensures it remains relevant and effectively supports the strategic objectives.

Table 11. Project-Oriented Approach Aligned with Gap Analysis
Section 1/4

Project: Testing/Enabling Facilities for R&D of critical technologies			
Goals	Implementation actions	Cross-cutting	Key SRIA Challenges & actions
Provide development and validation of physics scenarios and science & technology integration	Validation of power plant relevant scenarios in existing, early phase of operation (e.g. JT60-SA) or/under construction (e.g. ITER) devices Next step stellarator to close the gaps towards a stellarator FOAK Power plant relevant fuel cycle demonstration facility	Materials Remote handling Training & Knowledge transfer	5.3.1 Fusion Power Plant design and integration 5.3.2 Tritium Breeding Blanket 5.3.3 Tritium fuel cycle 5.3.4 Diagnostic & Control 5.3.5 Magnets and Cryogenics 5.3.6 Plasma Power and Particle Exhaust 5.3.7 Plasma Heating Systems (MCF)
Provide Breeding Blanket (BB) validation	Upgrade of IFMIF-DONES with a dual accelerator and Breeding Blanket Unit testing: assessment of modular validation strategies Cold tests of BB components (FW, etc.) in present and new EU devices as well as nuclearized test in EU fission facilities. Fuel cycle demonstration and qualification facilities		
Provide material validation and qualification	Upgrade of IFMIF-DONES with a dual accelerator Network of Hot Cells for material characterization Pulsed neutron source facility for ICF test components		
Provide power exhaust validation	Manufacturing of advanced PFC and tests under very long plasma duration (e.g. WEST, W7X). Upgrading DTT to full capability and testing advanced divertor configurations and materials in power plant relevant conditions.		

Table 11. Project-Oriented Approach Aligned with Gap Analysis
Section 2/4

Project: Testing/Enabling Facilities for R&D of critical technologies			
Goals	Implementation actions	Cross-cutting	Key SRIA Challenges & actions
Provide remote handling validation	Development of remote maintenance test facilities.	Materials Remote handling Training & Knowledge transfer	5.3.1 Fusion Power Plant design and integration
			5.3.2 Tritium Breeding Blanket
Provide heating system testing facility at industrial scale	Gyrotron test bed facilities		5.3.3 Tritium fuel cycle
			5.3.4 Diagnostic & Control
Management of tritiated waste, developing fusion acceptability	Building a dedicated device for developing tritiated waste processes		5.3.5 Magnets and Cryogenics
			5.3.6 Plasma Power and Particle Exhaust
Provide HTS validation	Development of HTS validation programmes (e.g. model coil), including development, operation and protection.		5.3.7 Plasma Heating Systems (MCF)
Instrumentation and Diagnostic Environmental Validation	Development of instrumentation and diagnostic technologies under relevant environment conditions (e.g. neutron, high temperature conditions)		
Provide First Wall Validation in ICF	Integrated First Wall component test under Pulsed Irradiation (e.g. GSI) Development of facilities for First Wall components		

Table 11. Project-Oriented Approach Aligned with Gap Analysis
Section 3/4

Project: Fusion Pilot Plant (MCF)*			
Goals	Implementation actions	Cross-cutting	Key SRIA Challenges & actions
Enhance the TRL of all systems to a level that enables the integrated design and construction of a First of a Kind (FOAK) Fusion Power Plant Fusion Pilot Plant serves as an intermediate step between large-scale experimental devices like ITER and FOAK.	Feasibility, conceptual and engineering designs R&D, testing and qualification of critical technologies in relevant fusion environment: magnets, BB, fuel cycle, remote maintenance, control systems, steady state plasma operation and auxiliary heating systems Integrated validation of BB and fuel cycle technologies under a fusion relevant scenario Development of power plant integrated scenarios towards commercialization Cost and manufacturability assessment towards commercialization Supply chain and manufacturing (e.g. Eurofer & ODS) Safety report and associate site specific activities Licensing process and regulation	Materials Remote handling Training & Knowledge transfer	5.3.1 Fusion Power Plant design and integration 5.3.2 Tritium Breeding Blanket 5.3.3 Tritium fuel cycle 5.3.4 Diagnostic & Control 5.3.5 Magnets and Cryogenics 5.3.6 Plasma Power and Particle Exhaust 5.3.7 Plasma Heating Systems (MCF)

* Currently under development - in the conceptual design phase - by EUROfusion

Table 11. Project-Oriented Approach Aligned with Gap Analysis
Section 4/4

Project: Inertial Implosion Facility (ICF)			
Goals	Implementation actions	Cross-cutting	Key SRIA Challenges & actions
Development of a direct-drive ignition-grade schemes - such as central hot spot ignition, shock ignition and fast ignition - to support the design of future ICF pilot plants	System design integration Develop a high-performance laser system for the implosion facility Develop industrial approaches to high-quality mass production of targets. Development of materials under pulsed neutron, ions and X-rays irradiation Supply chain and manufacturing (e.g. Eurofer & ODS) Management of burst mode operation, including target injection and metrology and debris handling Develop advanced simulation codes for laser-target interaction.	Materials Remote handling Training & Knowledge transfer	5.3.1 Fusion Power Plant design and integration. 5.3.4 Diagnostic & Control 5.3.8 Targets 5.3.9 High Performance Lasers

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**6. FUSION
INDUSTRIALIZATION
ENABLERS**

6.1. Fusion Energy Regulation

In the absence of a fusion-specific legal framework at the EU level, ensuring the effective and harmonized application of safety requirements across Member States remains challenging. As fusion technology continues to mature, the development of an adequate legal and regulatory framework will be essential to guarantee safety, facilitate innovation, and provide greater certainty for both regulators and developers/operators.

Currently, this topic is addressed by national regulatory authorities in coordination with ENSREG (European Nuclear Safety Regulators Group), the European Commission, and the International Atomic Energy Agency. Strengthened collaboration between regulatory authorities, industry, and research organizations is widely recognized as crucial for building the competence and capacity needed to address fusion-specific hazards. In this context, the European Commission is reinforcing its cooperation with ENSREG and continuing exchanges on regulatory aspects of fusion. To support this effort, an ENSREG Task Force on Fusion Energy has been established.

certainty for developers, operators, and regulators, to support the timely development of codes and standards, and to ensure the EU's competitiveness—especially as governments in the USA, UK, and China advance their own regulatory approaches.

Regulatory approaches to fusion facilities still vary significantly across countries. This divergence has practical consequences, as it tends to direct a greater share of private investment towards jurisdictions offering more predictable and proportionate regulatory frameworks.

While a comprehensive regulatory framework for a Fusion Pilot Plant is not immediately needed, clear guidelines on key principles are essential to provide

Challenges:

- 6.1.1.1. Difficulty in establishing a unified approach due to nation-specific regulations
- 6.1.1.2. Diversity of fusion power plant concepts (magnetic confinement, inertial confinement and different fuel types)
- 6.1.1.3. Risk of over-regulation (too prescriptive or overly conservative), due to limited regulatory experience in fusion and evolving safety culture
- 6.1.1.4. Concerns regarding nuclear proliferation

Actions:

- Support the development of common guidelines on key regulatory principles for a fusion power plant.
- Support the development of fusion specific codes and standards.
- Explore International Cooperation Frameworks.

6.2. Industrial Supply Chain Development

The EU's industrial fusion ecosystem has matured steadily over recent decades, with development largely anchored in the ITER program. Addressing the previously identified technology gaps will require developing and validating solutions across critical areas, including the fuel cycle, remote handling, heating systems, and plasma control, for a range of fusion concepts. A robust and resilient supply chain is essential for the development and deployment of fusion energy, as fusion facilities rely on highly specialized components, advanced materials, and complex manufacturing capabilities that must be delivered at scale and to stringent quality standards.

European industry already plays a leading global role in the design and manufacture of key components for fusion facilities. As fusion energy advances, it is expected to create significant market opportunities beyond the energy sector, stimulating growth in advanced materials, high-precision manufacturing, and energy storage technologies. By embedding fusion energy within its broader high-technology strategy, the EU can leverage these spillover benefits to drive innovation, strengthen industrial competitiveness, and create high-value jobs across multiple sectors.

Strengthening the European supply chain and closing critical technology gaps will require identifying key European stakeholders capable of serving as system integrators, responsible for coordinating the construction and operation of a future fusion power plant.

A robust supply chain will enable the transition from experiments to industrial deployment, mitigate bottlenecks and dependencies, drive cost reductions through standardization and industrial learning, foster innovation and industry engagement, and secure Europe's

strategic autonomy in the global fusion market. A resilient fusion supply chain depends not only on robust industrial capacity but also on the transfer of knowledge—from research to manufacturers, and across European suppliers.

The development of the industrial supply chain is critical to the deployment, advancement, and construction of key facilities, particularly the new infrastructure and upgrades required to develop, test, and validate integrated fusion technologies in fusion-relevant environments. In this context, the project-oriented actions outlined in Sections 5.3 (*Gap Analysis & Challenges*) and 5.4 (*Project-Oriented Approach Aligned with Gap Analysis*) play a central role.

Challenges:

- 6.2.1.1. Strengthen the EU Fusion Supply Chain
- 6.2.1.2. Foster Technology and Knowledge Transfer

Actions:

- Leverage the critical role of Small and medium-sized enterprises (SMEs), as key contributors in the EU ecosystem
- Foster comprehensive understanding of market dynamics and the involvement of utilities in early adoption strategies for fusion energy.
- Encourage staff exchanges between public and private organizations to drive innovation and enhance knowledge transfer.

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**7. SRIA
IMPLEMENTATION,
GOVERNANCE
AND EXPECTED
IMPACTS**

The implementation of the Strategic Research and Innovation Agenda (SRIA) will be carried out through close, structured interaction among three key pillars: the European Fusion Stakeholder Platform (EFSP), the Industry-Led Association (ILA), and the Public–Private Partnership (PPP).

The EFSP serves as a central hub for the European fusion ecosystem, bringing together a broad, diverse range of stakeholders and entities with an interest in fusion energy. It serves as a general advisory body in the fusion sector. The EFSP will continue to play an active role in the development and refinement of the SRIA, primarily by supporting the ILA and by providing targeted input on emerging topics from across the fusion ecosystem. FUSION NOW—the EU's Industry-Led Association (ILA) for fusion energy—will establish a Public–Private Partnership (PPP) with the European Commission (EC) under Euratom's co-programmed partnership model. As the representative body of industry, FUSION NOW shares ownership of the SRIA and will drive SRIA updates, integrating input from wider stakeholders through the EFSP. The objective of a co-programmed partnership is to accelerate technological readiness, foster collaboration between the public and private sectors, strengthen EU industrial leadership, and enable commercial fusion deployment. The PPP is formally established through a Memorandum of Understanding (MoU) between the EC and the ILA—FUSION NOW—defining its scope, governance, and commitments, including a Partnership Board and advisory committees for strategic oversight.

Under the Euratom Work Program 2026–2027¹, €77 million will support early PPP activities, focusing on high-maturity, commercially promising technologies aligned with the SRIA. Partner contributions will match EU funding, with expanded investment planned for the next Framework Program 2028–2034.

The PPP will elevate Europe's fusion industry from a collection of component suppliers to a unified, competitive ecosystem, driving innovation and technology transfer across the value chain. By aligning public and private efforts, it will maximize resource efficiency, accelerate commercialization, and reinforce EU leadership in fusion energy.

The governance structure of the PPP outlines how the co-programmed European partnership will be managed and coordinated, including the rules governing its operation, composition, and decision-making processes. The governance structure comprises a decision-making body comprising members of the EC and those nominated by the FUSION NOW Association. This body serves as the primary forum for dialogue and steering to achieve the objectives outlined in the MoU. Advisory bodies will be constituted to provide advice and support to the PPP decision-making bodies in the governance of the PPP, with the aim of achieving its objectives.

The primary expected impact of the PPP is to transform the role of the European fusion industry from its current position—where companies primarily act as suppliers of components—into a strong, consolidated industrial ecosystem capable of actively shaping a common

1 [Euratom Work Programme 2026-2027 for nuclear research and training](#)

European strategic agenda and competing effectively in the international fusion market. By fostering closer collaboration between industry, research institutions, and EU initiatives, the PPP aims to strengthen industrial capabilities, encourage technology transfer, and promote innovation across the entire fusion value chain. The partnership will also enable better coordination and the creation of synergies between the partners' own activities and EU-funded projects, thereby maximizing the impact of allocated resources and avoiding duplication of effort. This collaborative approach is expected to accelerate the development and deployment of key technologies, support the establishment of high-value industrial supply chains, and reinforce the EU's global leadership in fusion energy.

To ensure effective progress monitoring and to provide structured feedback on the outcomes of PPP projects to the European Commission, the Memorandum of Understanding (MoU) emphasizes the importance of defining Key Performance Indicators (KPIs). These KPIs (see Section 4.4.4) serve as measurable benchmarks to track advancements towards the SRIA objectives, evaluate the efficiency of the partnership's activities, and quantify the broader impact of the PPP on the EU industrial and technological landscape. By linking tangible performance metrics to strategic goals, the PPP will demonstrate accountability, guide decision-making, and ensure that investments deliver maximum value for the European fusion sector.

STRATEGIC RESEARCH &
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FUSION ENERGY IN EUROPE

2026

**8. CONCLUSIONS
AND OUTLOOK**

The Strategic Research and Innovation Agenda (SRIA) establishes an unprecedented shared strategic direction for fusion-related research and innovation in the EU. It provides a common vision that aligns stakeholders across the European fusion ecosystem, focusing efforts on impact-driven priorities designed to accelerate progress towards commercial fusion energy while strengthening the EU's technological leadership. Crucially, this direction is built on collaboration across the entire value chain—from research and technology development to industrial deployment and market readiness—and encourages engagement beyond the traditional fusion community, including related industries, policymakers, and investors.

The SRIA is designed as a flexible, adaptive strategic guide, helping coordinate efforts, identify synergies, and focus resources where they can generate the greatest impact. It provides orientation and coherence while preserving the flexibility needed for scientific breakthroughs, technological innovation, and market integration.

The SRIA evolves with the fusion landscape, ensuring its relevance by periodically incorporating new scientific insights, technological opportunities, and stakeholder perspectives—including those of industry, researchers, technology developers, policymakers, and society at large.

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TECHNICAL ANNEX

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AGENDA

Technical Annex

Gap analysis & challenges

This section identifies key technological gaps and proposes targeted actions to resolve them, guiding the EU's strategic R&I priorities.

Several gaps have been identified, building on the achievements and critical analyses of progress yet to be made, according to the European fusion laboratories and in consultation with the community through dedicated meetings. These meetings gather the most comprehensive fusion public and private stakeholder landscape, spanning both magnetic fusion (such as tokamaks, stellarators, and open/mirror magnetic systems) and inertial confinement fusion, as well as other approaches. Some of these gaps are common to both magnetic (MCF) and inertial (ICF) confinement fusion; addressing them will promote synergies between the two approaches, while fully accounting for their specific differences. In addition, sustained efforts in training and knowledge transfer are recognized as crucial for supporting all aspects of fusion R&D, helping to build the future workforce and foster innovation across the sector. The goal is to maximize synergies between various credible approaches while minimizing the risk of dispersing efforts and resources.

For each identified gap, the problem statement has been summarised, and specific challenges and proposed actions have been outlined. For each technology, Technology Readiness Levels (TRLs) have been assessed according to the following convention:

- “Low TRL” means TRL between 1-3 (from principle to experimental proof of concept). The identified gap is between fundamental research and applied research. Having reached this point, one can conclude that the technology is feasible from a scientific perspective.

- “Medium TRL” means TRL between 4-6. The identified gap is between advanced research and technology demonstration in a relevant environment (from components to prototype). It should be noted that this phase is sometimes referred to as the “valley of death”, due to the very high cost of testing the targeted technology in the operational environment.
- “High TRL” means TRL between 7-9 (from prototype to mass-produced product). The identified gap is in the phase of technological qualification and validation.

Effective coordination of concept development and the advancement of TRL for fusion energy, paired with clearly defined timescales, is essential. These timescales are categorized at three levels:

- Short Term (ST), before 2030
- Medium Term (MT), before 2035
- Long Term (LT), before 2040

This analysis should be pursued further, with fusion stakeholders aligning their efforts within existing EU legal and financial frameworks to accelerate the transition from basic technology research (TRL 1–2) to system testing and operation (TRL 8–9). In addition to TRLs, each action has been evaluated and assigned priorities based on three additional criteria:

a) Priority level based on action’s contribution to deploying fusion energy:

1. Indispensable (critical for deployment)
2. Accelerating (speeds up deployment)
3. Enabling (expands design space without acceleration)
4. Strategic (promotes EU autonomy in fusion science and technology)

b) Industry’s willingness to invest¹

Is the industry prepared to invest its own resources in the action (in kind and/or financial)?

1. Yes
2. No

c) Industry participation interest¹.

Does the industry intend to participate in the action?

1. Yes
2. No

The criteria (TRL and priority) described above and indicated for each action are based on an average of individual responses from participating stakeholders. While this approach provides a consensus-based view, it does not differentiate between stakeholder groups—such as supply chain participants or start-ups—whose expertise, interests, and strategic priorities may vary significantly. Given that MCF and ICF approaches are at different stages of development, the priority levels assigned to actions addressing specific gaps in MCF or ICF should be considered within their specific contexts.

¹ *Industry interest: if at least one industrial stakeholder (e.g., SME, energy utility or start-up) expresses interest in participation and/or investment, the response is recorded as “YES.”*

Actions 5.3.1

Table 1. Actions for gap Fusion Power Plant design and integration

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.1.1	Achieving a fusion plasma with the necessary parameters for energy production							
	5.3.1.1.1	Validation of burning plasma scenarios	L	M	MT	N	N	1
	5.3.1.1.2	Optimization of Stellarator configurations	L	M	MT	Y	Y	1
	5.3.1.1.3	ICF ignition validation in direct drive and optimization of implosion-ignition conditions	L	L	LT	Y	Y	1
5.3.1.2	Designing, based on credible fusion concepts, the fusion power plant with the lowest capital and Operation & Maintenance costs, and the highest efficiency and availability							
	5.3.1.2.1	Develop standards for engineering processes	L	H	ST	Y	Y	2
	5.3.1.2.2	Develop standards for manufacturing	M	H	ST	Y	Y	2
	5.3.1.2.3	Develop standards for quality management	L	H	ST	Y	Y	2
5.3.1.3	Maximizing overall plant efficiency by considering all influencing factors, from blanket temperature to the efficiency of the energy conversion process, the recirculated power fraction, and the lifetime of components							
	5.3.1.3.1	Develop advanced materials (ODS steels, SiC-SiC...) and systems, taking into account temperature, durability, manufacturability and availability, for improving power plant efficiency.	M	H	MT	Y	Y	1
5.3.1.4	Including manufacturability, reliability, availability, maintainability, and inspectability (RAMI); and economic and environmental attractiveness at the early design stage							
	5.3.1.4.1	Develop and implement waste management processes that minimize lifecycle environmental impacts and contribute to the sustainability of fusion power plants	L	M	MT	Y	N	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.1.4.2	Develop AI advanced fusion power plants technologies: a) Materials development b) Power plants integration c) Data management d) Quality control	L	M	ST	Y	Y	3
	5.3.1.4.3	Develop a global maintenance strategy for fusion power plant systems (i.e. maintenance on paper) including also design for maintainability, design for inspectability	L	M	MT	Y	Y	3
	5.3.1.4.4	Develop inspection technologies for as-build verification of design constraints and rapid inspection technologies in harsh fusion conditions (robots, drones...) to minimize downtime during operation.	L	M	MT	Y	Y	2
	5.3.1.4.5	Develop dedicated remote handling techniques as in-vessel components and pipe handling technologies for harsh fusion conditions.	L	M	MT	Y	N	3
5.3.1.5	Managing the different levels of maturity of fusion power plant components—which will increase during the design phase—with the potential for innovation or breakthrough unknown at the start-up date (mastering an evolving design throughout its operational life)							
	5.3.1.5.1	Develop robust and qualified simulation capabilities, including those for predicting the many complex interactions between plasma, components and engineering processes that take place within a fusion power plant (digital-twin)	L	M	MT	Y	Y	2
5.3.1.6	Mastering the high complexity arising from significant interdependencies between the large number of interconnected and complex systems, requiring compromises to tackle contradictory constraints							
	5.3.1.6.1	Develop system engineering & integration approach	L	H	ST	Y	Y	2
	5.3.1.6.2	Develop asset integrity procedures (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing devices	M	H	ST	Y	Y	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.1.7	Growing the industrial supply chain for fusion.							
	5.3.1.7.1	Develop a milestone-based approach for introducing reliability and safety in the initial phase of the industrial supply chain.	L	M	MT	Y	N	2
5.3.1.8	Applying the right safety rules to the right safety case and from the beginning of the design; fusion regulation is not yet stabilized and there is a risk to over-constrain the design space given the different nature of hazards							
	5.3.1.8.1	Develop / optimize safety cases w.r.t. the integral design concepts	L	M	MT	Y	N	2
	5.3.1.8.2	Address electromagnetic safety in ICF schemes	L	M	ST	Y	Y	1
5.3.1.9	Managing the reactive power and exchange at plant level							
	5.3.1.9.1	Develop and validate solutions to address the complex interactions within the power plant electrical system.	L	M	MT	Y	Y	1
5.3.1.10	Achieving a continuous and stable supply of electricity to the grid							
	5.3.1.10.1	Develop integral solutions that allow producing a continuous and stable supply of electricity to the grid, by controlling output and recirculating power or e.g. operating an energy storage system	L	M	LT	N	N	1

Actions 5.3.2

Table 2. Actions for gap Tritium Breeding Blanket and First Wall

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.2.1	Tritium delivery (production and release): to ensure T self-sufficiency of the plant and, potentially, provide the start-up inventory for further plants							
	5.3.2.1.1	Design breeding blanket solutions taking into account concepts based on different breeders to maximize the tritium breeding ratio	L	M	ST	Y	Y	1
	5.3.2.1.2	Improve & qualify BB first wall shielding materials & assemblies (W-based materials incl. optimized materials for accidental scenarios, W-EUROFER and W-advanced structural materials assemblies...) under fusion power plant neutron, ion, and gammas/X-rays irradiation, including the optimization of manufacturing processes	L	H	MT	Y	Y	1
	5.3.2.1.3	Construct facilities for testing BB assemblies (basic units and modules) under power plants -relevant conditions without neutrons (e.g., coolant loops) and with neutrons (neutron sources) to test the overall behavior up to relevant TRL's	M	H	ST	Y	Y	1
	5.3.2.1.4	Develop / optimize & qualify efficient tritium extraction processes from the BB: a) performing experiments with deuterium/tritium in dedicated facilities to compare the behavior of the different existing technologies (i.e. permeation against vacuum, gas liquid contactors, vacuum sieve tray...); b) developing specific models that reproduce the experiments and perform the scalability of the technique; c) demonstrating the scalability (in terms of manufacturability) from lab, to fusion power plant, constructing 1:1 prototypes	L	H	MT	Y	Y	1
	5.3.2.1.5	Develop components for reduction of tritium permeation and retention control (e.g. SiC/SiC layer)	L	M	MT	Y	Y	2
5.3.2.2	Heat recovery: to enable highly efficient electricity generation							

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.2.2.1	Design breeding blanket solutions taking into account different cooling concepts with improved efficiency, maintainability and reliability	L	M	ST	Y	Y	1
	5.3.2.2.2	Develop additive-manufactured ferritic-martensitic steel first-wall structures with conformal cooling channels	L	M	ST	Y	Y	3
	5.3.2.2.3	Improve durability of neutron resistant structural materials (RAFM-steels, ODS-steels, SiC/SiC, or any other material compatible with advanced liquid/molten salt breeder...) under fusion power plant relevant neutron fluences and temperatures, including industrial upscaling	L	M	LT	Y	Y	2
	5.3.2.2.4	Develop / optimize innovative breeding blanket design solutions for maximizing efficiency, maintainability and reliability. Demonstrate related systems operation at high temperatures while minimizing T ₂ losses.	L	M	MT	Y	Y	2
5.3.2.3	Reliability of operation: to avoid accidents and unplanned down-time of the plant							
	5.3.2.3.1	Develop / optimize safety cases w.r.t. the available integral BB design concepts and the related facilities	L	M	ST	Y	Y	1
	5.3.2.3.2	Develop simulation tools able to extrapolate neutron irradiation effects and first wall load effects between different operation conditions	L	M	MT	Y	Y	2
	5.3.2.3.3	Develop components as corrosion barrier (e.g. SiC) for blanket structures to enhance coolant compatibility and reduce corrosion-driven degradation	L	M	MT	Y	Y	1
5.3.2.4	Availability: combination of component lifetime and remote maintenance/replacement efficiency							
	5.3.2.4.1	Develop / optimize remote maintenance operation and plant logistics concepts w.r.t. the available integral BB design concepts	L	M	MT	Y	Y	1
	5.3.2.4.2	Develop ISI techniques in conjunction with defect assessment methodologies to predict lifetime and replacement of components	L	M	MT	Y	Y	3
	5.3.2.4.3	Develop asset integrity procedures for BB (design, technical and operation integrity) based on	L	H	ST	Y	Y	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
		experimental and industrial experiences and develop database using data of failures of the existing experiments.						
	5.3.2.4.4	Develop/optimize auxiliary systems for liquid breeders such as pumps, I&C, purification system, chemical and volume control systems.	L	M	MT	Y	Y	1
	5.3.2.4.5	Develop structural Interface Layers for Hybrid Joints (e.g. SiC) to mitigate mismatch stresses, protect against corrosion, improve lifetime of blanket/divertor assemblies.	L	M	LT	Y	Y	4
5.3.2.5	Structural and functional materials development and qualification							
	5.3.2.5.1	Conduct experiments on BB structural materials to achieve damage levels similar to those expected in a fusion power plant (neutron sources and corresponding PIE facilities)	L	M	LT	Y	Y	1
	5.3.2.5.2	Establish reliable databases of material properties with traceable, quality-screened data measured according to international standards.	L	M	LT	Y	Y	2
	5.3.2.5.3	Develop C&S for advanced materials, joining techniques and unprecedented operating conditions.	L	M	MT	Y	N	2
	5.3.2.5.4	Improve & qualify BB functional materials (Li-based breeder materials, neutron multipliers, anti-corrosion and anti-permeation coatings) under power plant-relevant neutron irradiation. Optimize manufacturing processes and establish industrial protocols to assure an affordable production	M	H	MT	Y	Y	1
	5.3.2.5.5	Develop integrated modelling tools to complement the qualification and validation of the different BB concepts	L	M	MT	Y	Y	2
	5.3.2.5.6	Corrosion testing of structural materials for construction of transport systems of BB-relevant fluids (e.g., PbLi, molten salts, etc.)	M	H	MT	Y	Y	1
5.3.2.6	Supply chain for specific fusion power plant materials							

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.2.6.1	Secure long-term beryllium suppliers and assess recycling for irradiated components used in fusion environment	L	M	MT	Y	N	3
	5.3.2.6.2	Develop / optimize & qualify efficient 6Li enrichment processes: identify the most feasible technique for isotope separation, attending to the scalability of the process and the environmental impact; to establish a regulatory framework to produce Li for fusion under nuclear standards (e.g. ISO); establish industrial protocols to assure an affordable 6Li production; produce trials according to the regulatory framework to demonstrate industrial capacity	L	H	ST	Y	Y	1
	5.3.2.6.3	Develop safe logistics, handling protocols and standards for radioactive or toxic materials.	M	H	MT	Y	N	3
5.3.2.7	Manufacturability by commercial techniques that allow standardization and cost & time savings							
	5.3.2.7.1	Develop manufacturing techniques (additive manufacturing, machining, welding, etc.) that allow producing components that meet fusion quality standards with cost savings	L	M	MT	Y	Y	2
	5.3.2.7.2	Develop at industrial scale manufacturing routes for complex blanket components	L	M	MT	Y	Y	2
	5.3.2.7.3	Establish standards for quality control and qualification for blanket components	L	M	MT	Y	N	2
	5.3.2.7.4	Mock-up for blanket welding validation	L	M	ST	Y	Y	2
5.3.2.8	FW sustaining very high heat flux and particle (X-rays, ions, neutrons) irradiations							
	5.3.2.8.1	Address pulsed particle damage and durability of First Wall and optical materials in ICF burst-mode experiments and modeling	L	H	MT	Y	Y	1
	5.3.2.8.2	Develop relevant components to protect the First Wall during transient and off normal heat and radiation loads	L	H	MT	Y	Y	1

Actions 5.3.3

Table 3. Actions for gap Tritium fuel cycle

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.3.1	Reaction chamber fueling techniques (different for magnetic and inertial confinement fusion)							
	5.3.3.1.1	Develop, qualify and optimize frozen DT pellet fabrication and injection technologies including diagnostics development (MCF)	L	H	MT	Y	Y	2
	5.3.3.1.2	Design, improve and qualify high frequency injection technology of DT targets, including both cryogenic and room temperature conditions, compatible with high-speed operations and supports mass target manufacturing (ICF)	L	M	ST	Y	Y	1
	5.3.3.1.3	Assess the potential transition from cryogenic to non-cryogenic targets and its implications for the design and operational requirements of ICF target injectors (ICF)	L	M	MT	Y	Y	1
	5.3.3.1.4	Improve systems for target metrology and, tracking in the chamber, and synchronization with laser operation (ICF)	L	M	ST	Y	Y	2
	5.3.3.1.5	Establish a staged approach to pellet testing and long-term stability optimization using integrated pellet testbeds (MCF)	L	M	ST	Y	Y	1
	5.3.3.1.6	Modelling and software developments (pellet creation, acceleration/injection, tube optimization, pellet–plasma interaction) (MCF)	L	M	ST	Y	Y	2
5.3.3.2	Tritium-compatible vacuum pumping							
	5.3.3.2.1	Improve and qualify tritium-compatible rough vacuum pumping technology	L	M	ST-MT	Y	Y	2
	5.3.3.2.2	Improve and qualify tritium-compatible primary vacuum pumping technologies incl. hydrogen selective pumps	L	M	MT	Y	Y	1
	5.3.3.2.3	Develop pump integration schemes into the fusion power plant (MCF)	L	M	LT	Y	N	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.3.2.4	Develop schemes for management of exhaust of gases (containing debris and tritium) from the interior of the chamber in a pulsed way, establishing the appropriate rate for those procedures (ICF)	L	M	ST	Y	Y	3
5.3.3.3	Hydrogen purification, isotope separation, recovery (from large gaseous streams, materials) and storage							
	5.3.3.3.1	Improve and qualify hydrogen (tritium, deuterium) purification and rebalancing technologies. Develop thermodynamic models that reproduce the H-isotope separation	L	M	ST	Y	Y	1
	5.3.3.3.2	Optimize real-time tritium detectors (room, wearable, water) for operations& safety, improve response time and sensitivity	L	M	MT	Y	Y	2
	5.3.3.3.3	Improve and qualify techniques for tritium recovery and monitoring of low/very low tritium concentrations from large gas streams	L	M	ST	Y	Y	1
	5.3.3.3.4	Develop and industrialize hydrogen-specific devices like Pd–Ag membrane modules or equilibrators catalyst beds	M	H	MT	Y	Y	2
	5.3.3.3.5	Development of modelling software for tritium transport simulation and fuel cycle design	L	M	ST	Y	Y	1
	5.3.3.3.6	Waste treatment and tritium recovery processes for PFCs, materials, water and gas exhaust	L	M	MT	Y	Y	2
	5.3.3.3.7	Develop facilities for qualification of components in tritium environment	L	M	MT	Y	Y	1
	5.3.3.3.8	Develop graded, goal-oriented EU framework and standards for tritium handling	L	M	ST	Y	Y	1
5.3.3.4	Minimize tritium release and tritium inventories across the entire process chain							
	5.3.3.4.1	Develop and qualify tritium permeation-barrier coatings and sealing boundaries, standardize permeation test protocols and consolidate EU database	L	M	ST	Y	Y	2
	5.3.3.4.2	Develop and optimize fuel cycle architecture to minimize tritium inventory in the overall tritium plant e.g. by including selective pumping	L	M	MT	Y	Y	1

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.3.4.3	Process simulation and accountancy model development and validation, incl. a shared H-isotope property database and non-destructive tritium detection in solids	L	M	ST	Y	Y	2
	5.3.3.4.4	Tritium accountancy: methods, software tools, high-flow measurement accuracy	L	M	MT	Y	Y	1
	5.3.3.4.5	Develop optimized reversible storage and transport concepts for tritium	L	M	ST	Y	Y	2
5.3.3.5	Continuous fuel cycle operation in steady-state fusion devices							
	5.3.3.5.1	Demonstrate the capability of continuous tritium fuel cycle operation and control with reduced processing times	L	M	ST	Y	Y	1
	5.3.3.5.2	Modell architecture of fuel cycle for continuous fusion power plant, show feasibility	L	M	ST	Y	Y	1
	5.3.3.5.3	Develop/optimize safety cases w.r.t. the available integral Tritium Fuel Cycle design concepts	L	H	ST	Y	Y	2
	5.3.3.5.4	Develop asset integrity procedures for fuel cycle (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing experiments	L	M	ST	Y	Y	2
5.3.3.6	Tritium external production, economically feasible to procure the necessary amount of tritium to start new machines							
	5.3.3.6.1	Develop a strategy for tritium supply for fusion applications	L	M	ST	Y	Y	1
	5.3.3.6.2	Explore tritium external production in fission reactors	L	M	ST	Y	Y	2
	5.3.3.6.3	Explore accelerator-based tritium production (e.g. lithium target + proton beam) as a backup strategy	L	M	LT	Y	N	3

Actions 5.3.4

Table 4. Actions for gap Diagnostic & Control

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.4.1	Overall plant diagnostic architecture providing all necessary information for operation and control systems, taking into account fusion power plant-specific constraints, including steady-state operations							
	5.3.4.1.1	Compile the minimum necessary control functions and the corresponding control strategies for the respective fusion power plants approach, despite current uncertainties about the physics basis	L/M	H	MT	Y	Y	1
	5.3.4.1.2	Develop to steady state operation the plasma control strategy based on an integrated architecture including plasma actuators and relevant plant subsystems	L	M	ST	Y	N	1
	5.3.4.1.3	Development of simulation tools and non-deterministic approaches for management of plasma instabilities for steady state operations.	L	M	ST	Y	Y	1
	5.3.4.1.4	Develop effective control methods and technologies to minimize the impact of Loss Off-site Power (LOOP) events on machine operation and ensure safety	L	M	MT	Y	N	1
5.3.4.2	In-vessel components with a high degree of reliability and durability, to ensure high overall plant availability. The typical lifetime of in-vessel diagnostic and control components should be well above the mean time between planned blanket replacements							
	5.3.4.2.1	Select required diagnostic and control methods with regards to their robustness in view of durable and reliable measurements for plasma control and performance, retracting vulnerable front-end components into protected areas	L	M	MT	Y	Y	2
	5.3.4.2.2	Development and qualification of materials for diagnostics	L	M	ST	Y	N	2
	5.3.4.2.3	Develop and test diagnostics for reliable plasma equilibrium control and reliable plasma performance measurements, with sensors providing signal long-term stability under relevant neutron irradiation (e.g. magnetics, neutron & gamma meas.)	L	H	MT	Y	Y	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.4.2.4	Bring wall conditioning techniques to maturity for power plant first plasma start-up or post-replacement start-up (control oxygen, water and other impurities by GDC, boronization)	L	M	MT	Y	N	3
	5.3.4.2.5	Development of techniques to replace diagnostics without turning off the machine.	L	M	LT	Y	Y	2
5.3.4.3	Advanced/intelligent control and data management techniques are required to optimize controllability, given the limitations of available diagnostics and actuators							
	5.3.4.3.1	Develop and test advanced control modules considering the detailed properties of the plasma scenario and of the machine, as well as sensors and actuator properties	L	M	MT	Y	Y	2
	5.3.4.3.2	Develop asset integrity procedures for diagnostics (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing experiments	L	M	ST	Y	Y	1
	5.3.4.3.3	Develop model-predictive plasma control algorithms integrated with a digital twin and AI applications to diagnostics and control systems algorithms integrated with a digital twin and AI applications to diagnostics and control systems	L	M	MT	Y	Y	1
	5.3.4.3.4	Develop and test event-driven processes to manage off-normal events, including event driven data buffering and data storage	L	M	LT	Y	N	3
	5.3.4.3.5	Develop real time 3-D magnetic field reconstruction diagnostics for stellarators using sparse sensors arrays & ML-assisted inversion	L	M	LT	Y	Y	3
	5.3.4.3.6	Assess the need of hypervisors as a mean of increasing software safety and security of the safety critical applications in embedded environments	M	M	LT	Y	Y	2
5.3.4.4	Instrumentations for control systems							
	5.3.4.4.1	Develop functional and architectural models for High speed interlock systems	L	M	ST	Y	Y	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.4.4.2	Select the required diagnostic/sensors for special systems (using tritium, liquid metals, molten salts, etc.) and develop the missing ones.	L	M	MT	Y	Y	2
5.3.4.5	Diagnostics to monitor and control interaction conditions and target-to-plasma/target-to-debris conversion processes, increase the gain to levels suitable for energy production and support the achievement of ignition							
	5.3.4.5.1	Develop and test laser-plasma instabilities and laser coupling diagnostics to control interaction conditions and target-to plasma / target -to-debris conversion processes	L	M	MT	Y	Y	1
	5.3.4.5.2	Development of laser beam synchronization and steering to injected target, including target tracking system and metrology	L	M	MT	Y	Y	2
	5.3.4.5.3	Real time diagnostics operating at high repetition rates.	L	M	MT	Y	Y	1
	5.3.4.5.4	Develop and test ultra-short radiation sources (ion, x-ray, neutron) for laser plasma diagnostics and material assessment	L	M	MT	Y	Y	2
	5.3.4.5.5	Develop diagnostics systems and electronics capable to withstand the huge Electromagnetic Pulses (EMP) which will be generated when the lasers fire on target.	M	H	MT	Y	Y	1
	5.3.4.5.6	Develop and test diagnostics for implosion and high gain physics	M	H	MT	Y	Y	3

Actions 5.3.5

Table 5. Actions for gap Magnets and Cryogenics (MCF)

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.5.1	Enhancing operating margins compared to LTS							
	5.3.5.1.1	Develop and test innovative superconducting materials (HTS) for advanced conductors and magnets	M	H	ST	Y	Y	4
	5.3.5.1.2	Develop and qualify HTS high current multi-tape conductors, including cooling scheme, that can reach several tens of thousands of amperes	M	H	ST	Y	Y	1
	5.3.5.1.3	Manufacturing and test of large-scale HTS model coil	L	M	ST	Y	Y	1
5.3.5.2	Reducing manufacturing and operating cost compared to LTS							
	5.3.5.2.1	Industrial scale-up of HTS (REBCO) tapes production	M	H	ST	Y	Y	1
5.3.5.3	Developing quench detection and protection for HTS							
	5.3.5.3.1	Develop active (e.g. current limiting devices, bypass systems) and passive systems (e.g. quench heaters) for quench protection	L	M	ST	Y	Y	2
	5.3.5.3.2	Develop a predictive HTS cooling model for anticipating quench protection	L	M	ST	Y	Y	2
	5.3.5.3.3	Develop advanced non-voltage magnetic safety systems for quench detection	L	M	ST	Y	Y	1
5.3.5.4	Developing remote maintenance scheme and magnet technology							
	5.3.5.4.1	Develop and test of dismountable joints for superconducting magnets to enhance remote maintenance and innovative assembly schemes	L	M	ST	Y	Y	1
	5.3.5.4.2	Develop and test flexible schemes for superconducting magnets to simplify manufacturing/construction (in situ winding, modularity, insulation approach, ...)	L	M	MT	Y	N	2
	5.3.5.4.3	Develop remote maintenance operation and plant logistics concepts w.r.t. the available magnet concept	M	H	MT	Y	Y	1

			TRL			Industry's interest		
Ch. ID	Action ID	Action description	present (L-M-H)	target (L-M-H)	Timescale (ST-MT-LT)	participation (Y/N)	investment (Y/N)	Fusion Priority (1-4)
5.3.5.5	Advanced Instrumentation and cryogenics for magnets							
	5.3.5.5.1	Increase the efficiency of HTS magnet power systems	L	M	ST	Y	Y	1
	5.3.5.5.2	Demonstrate gas-cooled cryogenic system for LTS and HTS coils to halve cryoplant power	L	M	MT	Y	Y	2
	5.3.5.5.3	Alternative cryogenics based on hydrogen or cryogen-free system, to reduce the use of limited resource of helium	M	H	MT	Y	Y	2
	5.3.5.5.4	High power transmission lines (Superconducting links) for energizing high field magnets (forecasted with hundreds or thousand of amperes) and associated cryogenics solutions	L	M	MT	Y	Y	2
	5.3.5.5.6	Develop asset integrity instruments and procedures for diagnostics (design, technical and operation integrity) based on experimental and industrial experiences and develop database using data of failures of the existing experiments	L	M	ST	Y	Y	1
5.3.5.6	Developing integrated validation programme for fusion power plant HTS magnets							
	5.3.5.6.1	Develop mockups (cable, windings, double pancake, model coils, etc.) for validating the HTS magnets technology	M	H	ST	Y	Y	1
	5.3.5.6.2	Develop the conceptual design of a cryoplant capable of cooling down the magnetic system of a HTS-based fusion power plant	M	H	ST	Y	Y	2
5.3.5.7	Improving of the radiation resistance of LTS and HTS coils							
	5.3.5.7.1	Assess under fusion relevant conditions radiation tolerance and dose limits for HTS materials and insulators	M	H	ST	Y	Y	1

Actions 5.3.6

Table 6. Actions for gap Plasma Power and Particle Exhaust (MCF)

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.6.1	Developing suitable configurations to maximize power and particle exhaust, addressing plasma–wall interactions (first wall and divertor) in an integrated manner, and implementing the testing program							
	5.3.6.1.1	Implementing novel divertor designs to enhance the distribution of the heat flux, thus reducing peak loads on any specific part of the power plant and to allow enhanced particle exhaust	L	M	MT	Y	Y	1
	5.3.6.1.2	Implementing novel divertor designs to ensure wall protection without significant impact on TBR, maintainability, availability & cost. (incl. liquid metal-based limiter), minimize rad-waste disposal and simplify refurbishment of sacrificial targets.	L	M	MT	Y	Y	1
	5.3.6.1.3	Developing an integrated virtual design platform to couple Multiphysics engineering simulations with power/particle exhaust physics analyses aiming at a physics-informed rational design scheme	L	M	MT	Y	Y	2
	5.3.6.1.4	Design & test modular pumped divertor with liquid SnLi plasma facing surface for ≥20 MW m ⁻² heat flux	L	M	MT	Y	Y	2
	5.3.6.1.5	Develop test facilities and perform divertor testing and qualification in power plant relevant conditions	L	M	MT	Y	Y	1
5.3.6.2	Developing and qualifying structural and functional materials capable of withstanding very high heat fluxes and neutron fluences without compromising their physical and structural integrity							
	5.3.6.2.1	Improving neutron resistance of divertor materials and components under fusion power plant relevant neutron irradiation (e.g. IFMIF-DONES)	L	M	MT	Y	Y	2
	5.3.6.2.2	Development and qualification of advanced materials having high thermal conductivity (e.g. K-doped W, W-Cu composites and ODS-Cu) capable of withstanding high heat fluxes and neutron loads, including materials that can self-repair damage due to neutron irradiation, and those based on liquid metals.	L	H	MT	Y	Y	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.6.2.3	Establish reliable databases of material properties with traceable, quality-screened data (including neutron-irradiation/post-irradiation test data) measured according to international standards, and develop C&S for advanced materials, joining techniques in unprecedented operating conditions	L	M	MT	Y	Y	2
	5.3.6.2.4	Develop structural integrity assessment methodologies in conjunction with HHF design-by-experiment testing	L	M	MT	Y	Y	3
	5.3.6.2.5	Qualifying the baseline HHF technology (ITER-like W monoblock type targets) by means of neutron-irradiation/post-irradiation HHF test & in-situ tokamak plasma exposure test (leading edge loads)	M	H	LT	Y	Y	1
5.3.6.3	Developing manufacturing techniques and industrial upscaling processes capable of ensuring the required system functions in the power plants operating conditions, including additive manufacturing							
	5.3.6.3.1	Implementing advanced and optimized joining techniques for the chosen materials, focusing on achieving high-quality, durable joints capable of withstanding the operational conditions	M	H	MT	Y	Y	2
	5.3.6.3.2	Implementing advanced manufacturing technologies for pressurized or structural steel components with complex geometry (e.g. cassette body, supports) focusing on achieving high-quality and up-scaling to full-scale prototype dimensions	L	M	MT	Y	Y	2
	5.3.6.3.3	Implementing advanced non-destructive test (NDT) techniques and data evaluation methodology for inspection to detect defects/cracks and residual stress in as-manufactured prototype components	L	M	MT	Y	Y	2
5.3.6.4	Achieving plant availability by addressing the combination of component lifetime and remote maintenance/replacement efficiency							
	5.3.6.4.1	Implementing optimal design and conditions for ramp-up and ramp-down phases, thus, to reduce peak heat and impurity particle flux production in this phase	L	M	LT	Y	Y	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.6.4.2	Implementing "marker" layers in PFC components at critical locations for transient or steady-state erosion to identify passively (spectroscopy) or actively (laser-techniques) if repair/replacement action is required.	L	M	LT	Y	Y	2
	5.3.6.4.3	Bring in-situ repair/recovery techniques for most critical PFCs to maturity (laser-repair or plasma-spraying)	L	M	LT	Y	Y	2
	5.3.6.4.4	Develop ISI techniques in conjunction with defect assessment methodologies to predict lifetime and replacement of components.	L	M	LT	Y	Y	2

Actions 5.3.7

Table 7. Actions for gap Plasma Heating Systems (MCF)

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.7.1	Industrialization and adaptation to power plants of today's heating systems, including steady-state operation requirements							
	5.3.7.1.1	Develop and design high frequency (170 – 300 GHz), multifrequency, high power (1 to 2 MW), lower TCO, steady state gyrotrons with high efficiency (> 50%), manufacturability and reliability	M	H	ST	Y	Y	2
	5.3.7.1.2	Develop industrial test benches for gyrotrons qualification and conditioning	L	H	ST	Y	Y	2
	5.3.7.1.3	Develop complete ECRH system integrating all components	M	H	ST	Y	Y	1
	5.3.7.1.4	Develop fast installation mechanisms, intelligent control and adjustment systems to reduce installation time and operate gyrotrons at optimum operating points	M	H	ST	Y	Y	1
	5.3.7.1.5	Increase the production capacity of gyrotrons	M	H	ST	Y	Y	1
	5.3.7.1.6	Maintain expertise, know-how & industrial capability on ECRH & ICRH	M	H	ST	Y	Y	1
	5.3.7.1.7	Develop high efficiency and compact Power Supplies for Gyrotrons (MHVPS; BPS; APS)	M	H	ST	Y	Y	1
	5.3.7.1.8	Develop Additive Manufacturing of high precision mechanical components	M	H	ST	Y	Y	1
5.3.7.2	Operational efficiency of today's heating systems in terms of wall-plug efficiency							
	5.3.7.2.1	Develop ECRH transmission line technology for output power levels > 1MW	M	H	ST	N	Y	2
	5.3.7.2.2	Develop high efficiency (>50%) neutral beam injectors (neutralization system, pumping systems, RF ion sources), possibly via alternative concepts	L	H	LT	Y	Y	2
	5.3.7.2.3	Develop ICRH power sources of high efficiency, in the frequency range 40-120 MHz, targeting 2 to 3 MW, possibly based on solid state technology	L	H	MT	Y	Y	4
5.3.7.3	Reliability, availability and lifetime of today's heating systems							

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
	5.3.7.3.1	Explore quasi-optical transmission technology	L	M	LT	N	N	4
5.3.7.4	Nuclear compatibility of RF launcher components/concepts							
	5.3.7.4.1	Develop and test steady-state, high-heat-flux, radiation resistant and maintainable IC and EC RF launcher components, targeting a power per launcher of 30 to 50 MW, including appropriate steering mechanism (mechanical steering, remote steering and frequency steering) resistant to high neutron flux	L	M	MT	Y	Y	2
	5.3.7.4.2	Develop and test functional materials for power windows and mirrors application in a representative power plant environment, including advanced diamond windows and window assemblies with lower losses for higher output power and for broadband operation respectively	L	M	LT	Y	Y	3
	5.3.7.4.3	Development of optimal control strategy of RF plasma heating (ICRH, ECRH, EBW, LHH) to sustain heating plasma and steady state operation	M	H	ST	Y	Y	1

Actions 5.3.8

Table 8. Actions for gap Targets (ICF)

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.8.1	Develop requirements for advanced direct drive schemes and develop robust, high-efficiency and low-cost targets							
	5.3.8.1.1	Assessment of target characteristics in advanced Direct-Drive schemes	L	M	MT	Y	Y	1
	5.3.8.1.2	Design and test high-gain targets compatible with high-speed operation (10 Hz) with optimized architecture (density gradients between materials) / implosion speed / cold fuel entropy and compression levels/laser temporal waveform	L	M	MT	Y	Y	1
	5.3.8.1.3	Develop and validate robust simulation codes to predict target performance, emitted particles, radiation spectra and debris emission	L	M	MT	Y	Y	1
	5.3.8.1.4	Design and test facilities and structures for a European DD-ICF implosion facility that minimize required coolant flow, generate required T2, withstand the produced pressures, and achieve the required repetition rate, for application to an ICF power plant design	L	M	MT	Y	Y	1
	5.3.8.1.5	Address the management of burst-mode operation, including control of interaction conditions and target-to-plasma/target-to-debris conversion processes in DD-ICF	L	M	MT	Y	Y	2
5.3.8.2	Assess feasibility of using solid-state non-cryogenic targets							
	5.3.8.2.1	Assessment of solid-state non-cryogenic targets including low-tritium content targets and self-breeding targets for ICF (containing lithium)	L	M	LT	Y	Y	4
5.3.8.3	Develop requirements for target quality, cost and materials							
	5.3.8.3.1	Assessment of requirements for target quality, cost and materials, in relation with technologies developed in the industry, for an implosion facility, with prospective view for a power plant	L	M	MT	Y	Y	2

Ch. ID	Action ID	Action description	TRL		Timescale (ST-MT-LT)	Industry's interest		Fusion Priority (1-4)
			present (L-M-H)	target (L-M-H)		participation (Y/N)	investment (Y/N)	
5.3.8.4	5.3.8.3.2	Assessment of micro-structured materials (foams) impregnated with liquid DT, as alternative to solid DT	L	M	ST	Y	Y	1
	5.3.8.3.3	Assessment of nano-and micro-structured materials (foams) as advanced ablators in the target design to improve laser-plasma coupling and for mitigation of laser imprint and hydrodynamic instabilities	L	M	ST	Y	Y	1
	Assess and improve material properties to address ICF requirements							
	5.3.8.4.1	Assessment and optimization of material properties to address ICF requirements. Application of additive manufacturing techniques	L	M	ST	Y	Y	1

Actions 5.3.9

Table 9. Actions for gap High Performance Lasers (ICF)

			TRL			Industry's interest		
Ch. ID	Action ID	Action description	present (L-M-H)	target (L-M-H)	Timescale (ST-MT-LT)	participation (Y/N)	investment (Y/N)	Fusion Priority (1-4)
5.3.9.1	High-performance megajoule-class lasers with efficient coupling to the target for direct-drive implosion facilities							
	5.3.9.1.1	Identify and examine functional modular laser blocks in terms of parameters required for operation in burst mode and at 10 Hz	L	M	ST	Y	Y	1
	5.3.9.1.2	Assess the current status, availability, limits (performance, TRL, cost, reliability) of required diode-laser pump technology, develop and test advanced diode-pumped laser modules and systems, and establish the roadmap enabling scalable industrial diode-laser pump technology.	L	M	ST	Y	Y	1
	5.3.9.1.3	Develop larger bandwidth laser and beam-shaping technologies to enhance laser-plasma coupling and ensure highly uniform energy delivery to the target	L	M	MT	Y	Y	1
	5.3.9.1.4	Develop schemes for effective dynamical modification of laser focusing during direct-drive compression	L	M	ST	Y	Y	1
	5.3.9.1.5	Identify and assess solutions for increasing wall-plug efficiencies above 10%	L	M	ST	Y	Y	2
	5.3.9.1.6	Definition of a design of the laser system for a direct-drive implosion facility operating in burst mode, with identification of key factors for repetition rate operation up to an intermediate pulse energy level to address power plant level issues.	L	M	ST	Y	Y	1
5.3.9.2	Modular structure of the full-scale laser							
	5.3.9.2.1	Definition of specifications for the parameters of the main staged laser, and of the interconnections between the modular sub-stages	L	M	ST	Y	Y	1
	5.3.9.2.2	Develop alternative laser approaches towards MJ energies on target and schemes for synchronization of high-power laser systems (broadband, short-pulsed) on target	L	M	LT	Y	Y	2

			TRL			Industry's interest		
Ch. ID	Action ID	Action description	present (L-M-H)	target (L-M-H)	Timescale (ST-MT-LT)	participation (Y/N)	investment (Y/N)	Fusion Priority (1-4)
5.3.9.3	Laser design for high wall-plug efficiency, high repetition rate, and low maintenance cost to achieve ICF power plant performance							
	5.3.9.3.1	Identification of solutions to scaling limitations of the laser system defined for the burst mode implosion facility to be in line with a proposed power plant level capable laser design	L	M	LT	Y	Y	3
	5.3.9.3.2	Definition of a risk management process for critical components, including performance and cost scaling of diode laser pump supply, large optics and gain material	L	M	ST	Y	Y	3
5.3.9.4	Beam transport and optics							
	5.3.9.4.1	Definition of requirements and solutions for beam and final optic protection from vapor, debris and radiation	L	M	MT	Y	Y	1
	5.3.9.4.2	Definition of requirements and solutions for operation of beam transport and optics with vibration protection, over long periods and without substitution.	L	M	MT	Y	Y	1
	5.3.9.4.3	Develop methodologies and systems for stable, accurate and long-term operation of laser beam steering at MJ levels in burst mode.	L	M	LT	Y	Y	2

Actions 5.3.10

Table 10. Actions for gap Training, Knowledge Management

Ch. ID	Action ID	Action description	Industry's interest		Fusion Priority (1-4)
			participation (Y/N)	investment (Y/N)	
5.3.10.1	Develop continuous education and training programs related to the various fusion technologies (including nuclear safety) and fusion device operation. Connect academia, industry, and research laboratories for such training programs				
	5.3.10.1.1	Development of internship programs where students can work on industry projects through partnerships between public and private companies	Y	Y	2
	5.3.10.1.2	Increase fusion-related content in the University studies	Y	N	3
	5.3.10.1.3	Coordinate with European fusion education and training entities that have already established links between academia, research centres and industry; i.e., FuseNet, EUROfusion.	Y	N	4
	5.3.10.1.4	Maintain and develop a fully European, international master programme entirely dedicated to fusion as a supplier of engineers and master and PhD students for public and private R&D. This programme should become a hub for fusion teaching at the master level	Y	Y	1
	5.3.10.1.5	Set up a programme in charge of matchmaking between fusion education programmes at the master level and private/public entities which propose jobs, internships, theses or placements. This programme should also have scholarships for the students	Y	Y	2
5.3.10.2	Create job opportunities for fusion-skilled talent in the private sector, attract new talent from various disciplines, and promote long-term career development				
	5.3.10.2.1	Work on legal framework to ease temporary missions of skilled public officers to the industry	Y	N	4
	5.3.10.2.2	Establish European Fusion Technology Academy with industry placements on HTS<S magnets, materials, tritium tech & robotics	Y	Y	3
	5.3.10.2.3	Create rotational fellowship programme between fusion companies, public research, and technology institutes in fusion & suppliers for cross-training engineers and scientists	Y	Y	3
	5.3.10.2.4	Develop and/or sponsor activities focusing on new talent attraction at a local and European level; i.e., student competitions, job fairs, recruitment events. Training and upskilling programmes for workers including accesibility to fusion machines	Y	Y	4

			Industry's interest		
Ch. ID	Action ID	Action description	participation (Y/N)	investment (Y/N)	Fusion Priority (1-4)
5.3.10.3	Involve industry partners in fusion device design, manufacturing, integration, operation, and maintenance via research laboratories: to transfer laboratory know-how and develop industrial methods in this domain				
	5.3.10.3.1	Fund contracts in which industry will operate and maintain experimental fusion devices in the research labs	Y	N	2
5.3.10.4	Maintain state-of-the-art research infrastructures and establish testing facilities (fusion devices, material test platforms, etc.), associating them with training programs and promoting knowledge transfer to industry. Involve industrial partners from the early design phases of fusion systems to facilitate effective technology transfer				
	5.3.10.4.1	Maintain funding of state-of-the-art research infrastructures in the public labs and increase their links to the training program and to the industry	Y	N	2
	5.3.10.4.2	Develop education and training platforms for knowledge transfer and workforce training	Y	Y	1

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