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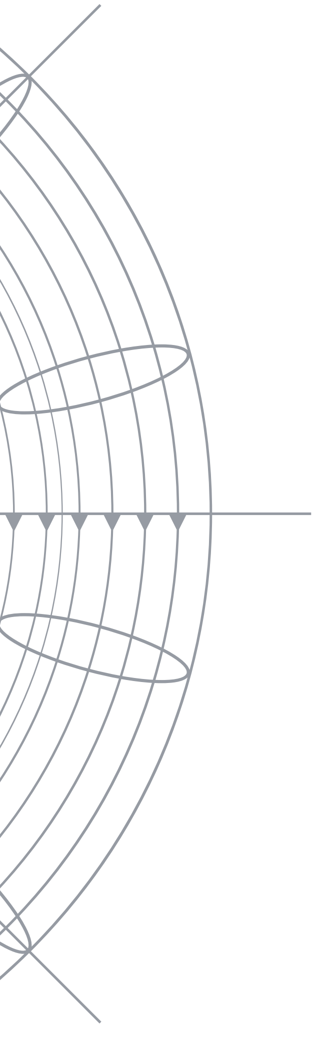
# Fusion Key Elements

A shared vision for fusion energy development



# Fusion Key Elements

## A shared vision for fusion energy development

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2024

# FOREWORD

Fusion energy as a potential long term sustainable clean energy solution for the world has been on the horizon for decades. Not anymore. New momentum arising from recent developments in the fusion sector makes deployment of fusion plants in the near future increasingly plausible.

Propelled by national and international programmes such as the ITER project, the sector is now experiencing an unprecedented transformation. Scientific breakthroughs, combined with a remarkable surge in private sector investment, have catalysed this transformation. In my engagements, I have observed a lot of excitement, passion and confidence among scientists and engineers who are pursuing many innovative ideas for deploying fusion energy systems. In a world grappling with the twin challenges of climate change and energy security, the emergence of a new clean energy source will be critical for a long term solution.

In addition, I have noted keenness among the key players to cooperate and share experience, knowledge and resources in a meaningful way to resolve remaining issues and develop an industrial base for sustainable fusion energy development. To facilitate this, it is important that all stakeholders involved in the development of fusion energy share a common vision and understanding of the path leading to commercialization of fusion energy. With these objectives in mind, this IAEA publication has identified a set of fusion key elements that will continue to provide a comprehensive road map and

invaluable guidance to scientists, engineers, regulators, entrepreneurs and policymakers worldwide in the future, where fusion energy plays a central role in our global energy landscape in the short and medium term.

The publication delves into the core aspects necessary for realizing this vision. The document is structured around six pivotal elements, each addressing crucial facets of the fusion energy paradigm. These include research, development and demonstration priorities and metrics, and commercialization milestones; resources, workforce and knowledge management; safety, security and non-proliferation; global collaboration; stakeholder roles; and public engagement. Together, these elements form the backbone of a cohesive strategy to navigate the complexities and seize the opportunities inherent in fusion energy development.

The IAEA is grateful to all those who contributed to this publication, including members of the International Fusion Research Council and other international experts and reviewers, for their valuable contributions and commitment to issue this publication in such a short time. The IAEA remains steadfast in its support of fusion energy development, championing initiatives that bring us closer to realizing the dream of limitless, clean energy. Together, let us embrace the promise of fusion energy, forging a path towards a brighter, more sustainable future for all.

Rafael Mariano Grossi
IAEA Director General

# INTRODUCTION

The pursuit of fusion energy is gaining momentum globally, as fusion technology promises to be an abundant, clean and sustainable solution for our future energy needs. Until recently, fusion energy development was primarily driven by national and international programmes, such as the ITER project. However, a significant shift has occurred, driven by the urgent need for clean energy sources to combat climate change and ensure energy security. Recent breakthroughs in fusion science and technology, coupled with substantial private sector investment, have rapidly transformed the fusion energy landscape. Public sector efforts in advancing fusion energy towards practical application are now being supplemented by a remarkably expanded private sector, which boasts over 40 active companies and more than US $7 billion[1] in investments, prioritizing commercialization efforts.

Despite their diverse technological approaches and financing arrangements for the development of fusion energy, the public and private sectors share a common objective: to make fusion a viable and sustainable energy source. This shared goal underscores the importance of increased collaboration between governments and private entities, which is crucial for accelerating the transition from research to commercialization.

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[1] Status as of July 2024 [1].

While these developments have injected optimism about the realization of fusion energy in the near future, several research, development and demonstration (RD&D) areas still require further progress. Additionally, for the successful adoption and deployment of fusion energy, it is necessary to expand the industrial base, develop global supply chains, build a competent workforce, have clear legal and regulatory guidelines and secure public support – all of which require cooperative multi-stakeholder engagement.

In such a rapidly evolving sector, cultivating a common understanding of key considerations surrounding fusion energy is essential. This understanding encompasses everything from research and development to deployment and commercialization, forming the foundation for navigating the complexities and opportunities of the fusion energy landscape. This publication provides a comprehensive overview of the six key elements necessary for a shared vision in fusion energy development, thereby facilitating a unified approach to advancing fusion as a cornerstone of future energy solutions.

# The six fusion key elements

**1.** RESEARCH, DEVELOPMENT AND DEMONSTRATION – page 8

**2.** INDUSTRIALIZATION – page 14

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# ONE GOAL

to make fusion a viable and sustainable energy source

# 1.

# **Research, development and demonstration** priorities and metrics, and commercialization milestones

Commercialization of fusion energy requires further progress in related scientific and technological areas. Continued support of research and development activities is essential for accelerating the demonstration and deployment of fusion plants and for developing supply chains.

# Research, development and demonstration priorities and documenting progress

In addressing the areas requiring further progress, it is crucial to differentiate the maturity levels of the various components of a fusion plant and their integration into a cohesive system capable of commercially viable energy production.

The essential areas of RD&D at low technology readiness level[2] (TRL) for establishing a fusion plant are pinpointed below. While each area is crucial, the development of materials resilient to extreme conditions and the tritium fuel cycle are regarded as the most urgent needs to enable deuterium–tritium (D–T) based fusion energy production.

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[2] Technology readiness levels provide a standardized and objective method for evaluating the maturity of different technologies and their different components.

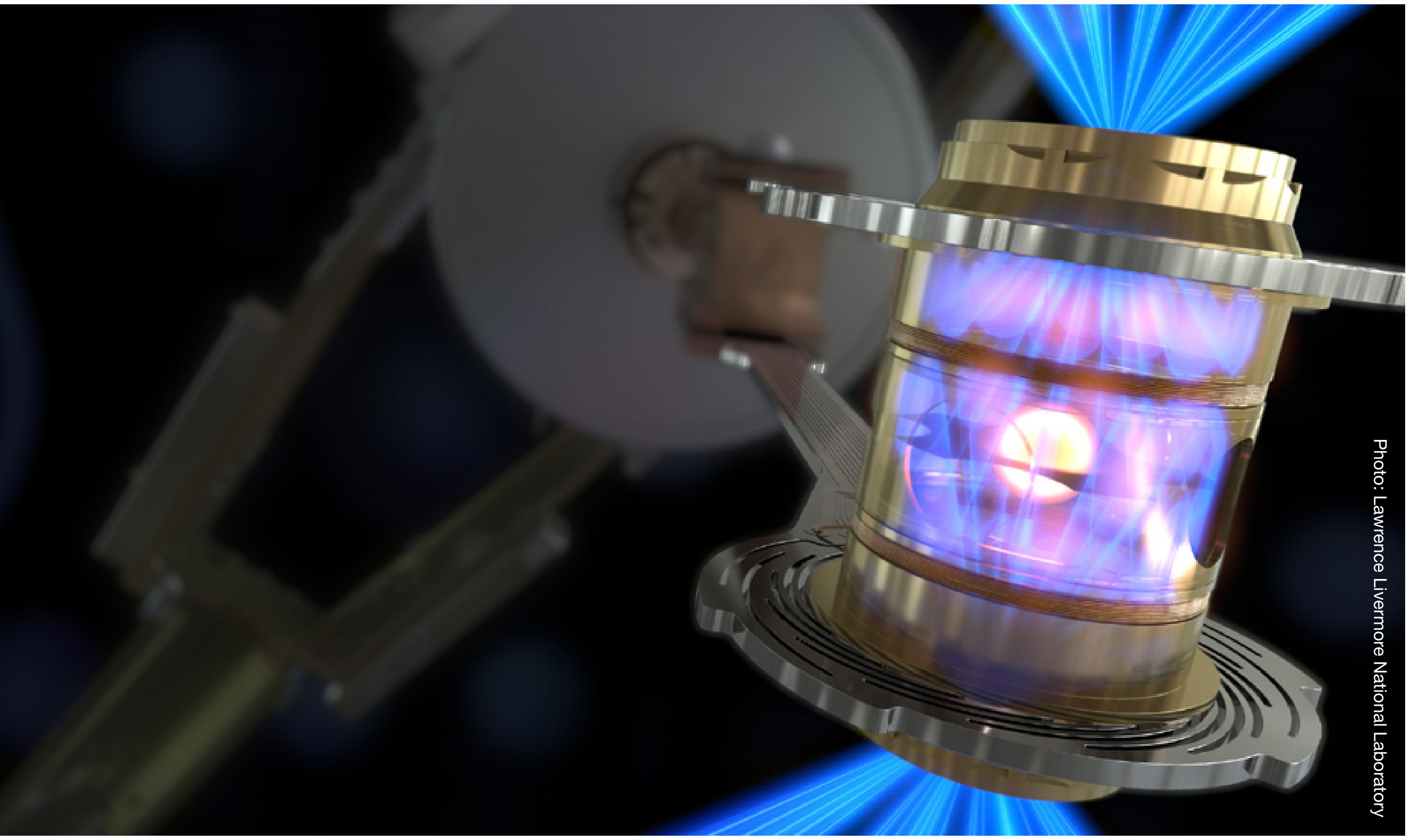
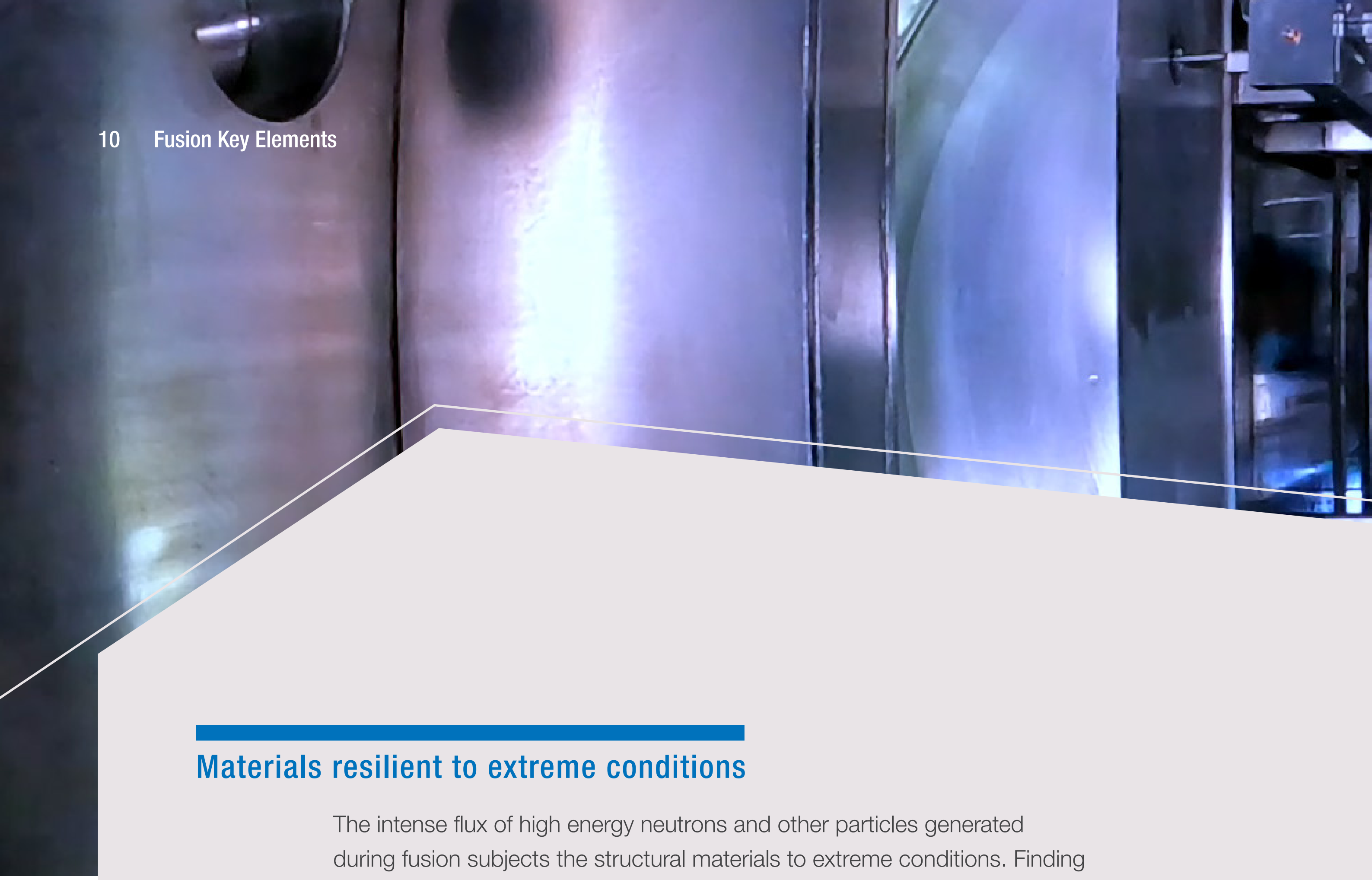


Photo: Lawrence Livermore National Laboratory



## Materials resilient to extreme conditions

The intense flux of high energy neutrons and other particles generated during fusion subjects the structural materials to extreme conditions. Finding materials capable of better withstanding these conditions while maintaining structural integrity and acceptable levels of activation is a top priority to improve the commercial viability of fusion. These materials also need to be compatible with maintaining plasma purity and with the challenging thermal, radiation and vacuum conditions inside the fusion machine. Innovative concepts, such as liquid first walls, could have the potential to relax certain requirements on structural materials. It is also important to address the potential effects of these extreme conditions on various other materials, including those used in breeding blankets, diagnostics, heating systems, remote handling systems and divertors, and to consider a range of material properties beyond just mechanical characteristics.

## Tritium fuel cycle

Tritium, a radioactive isotope of hydrogen, is a key fuel for D–T fusion plants. However, tritium has a relatively short half-life (12 years) and is not naturally abundant. Developing efficient tritium breeding and extraction techniques is essential to triggering and then sustaining fusion energy production in a D–T fusion plant.

Photo: Institute of Plasma Physics Chinese Academy of Sciences

## Power exhaust management

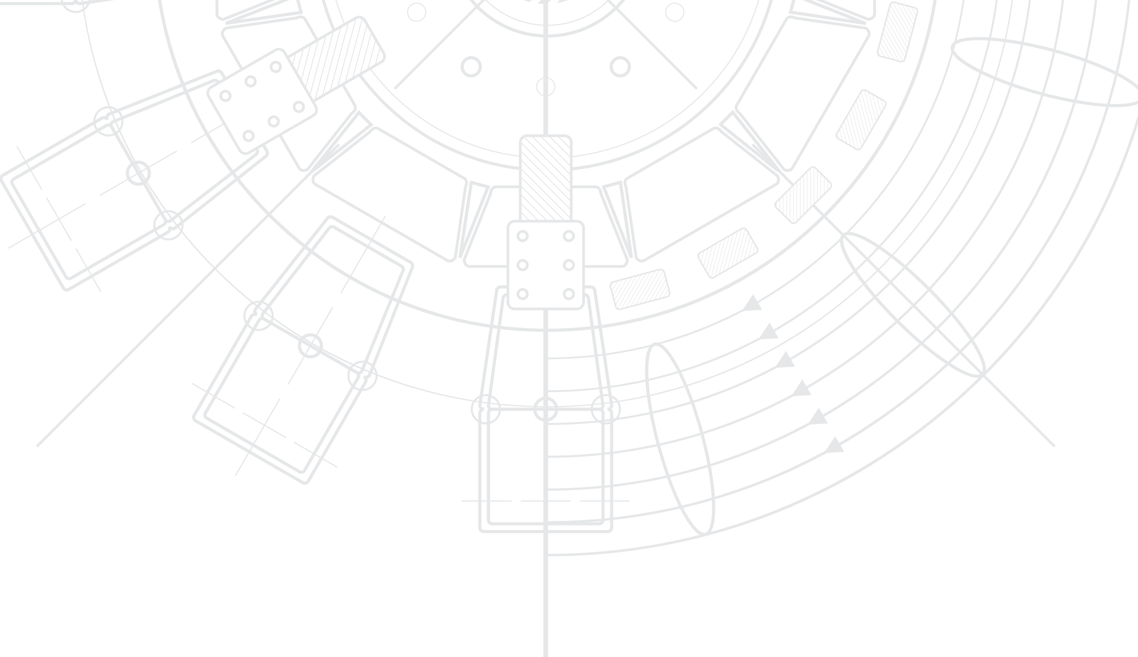
One of the primary challenges in fusion plants will be managing the heat and particle exhaust from the plasma. For magnetic confinement approaches, there is the additional challenge of steady-state plasma–material interactions. The extreme power density conditions foreseen in fusion plants present significant engineering challenges in plasma facing materials, cooling techniques and component design, among others. Advancing research on suitable plasma regimes remains a key experimental need.

## Remote handling

Fusion plants operate in harsh environments that are inaccessible to human operators. As a result, maintenance and repair tasks could require remote handling. It is necessary to maintain ongoing development efforts on these remote handling systems, including using advanced robotic systems, for commercial fusion energy applications.

## Heat extraction

The energy generated inside the fusion plant needs to be extracted efficiently and the corresponding components need to be sufficiently available in order to obtain a competitive cost of electricity. For concepts that utilize a steam cycle, the thermodynamic efficiency of the plant will increase if the blanket can operate at higher temperatures, for which reduced activation materials are needed.



Most fusion energy concepts share the same RD&D considerations, with some additional areas of development required which are specific to the confinement technology[3] and fuel choice[4]. After increasing the TRL of the discussed areas, the successful commercialization of fusion energy requires design optimization and validated components (e.g. radiation tolerant materials, radiation hardened sensors) in a fusion plant environment, considering safety and economic constraints from the earliest stages. This includes developing integrated solutions that combine burning plasma science, confinement technology, heat management and shielding.

A concerted effort is essential across the RD&D and integration areas highlighted above. Leveraging advances in technology — such as high performance computing, artificial intelligence and advanced manufacturing — can accelerate the advancement of fusion energy, paving the way for broader commercialization. Moreover, developing the necessary infrastructure (such as facilities, systems and frameworks) to support the entire lifecycle of fusion energy is vital for its successful commercialization.

Finally, as fusion energy moves from development to demonstration and deployment, it is important for both existing and emerging stakeholders in the fusion energy sector to properly document and share new results. Following traditional methods such as implementing peer review processes, ensuring transparency in communications about progress, protecting intellectual property where applicable and effectively engaging with governments, investors and the public through strategic communication are all essential steps.

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[3] For example, for inertial confinement fusion, key RD&D areas also include economical scale-up of driver and target technologies.

[4] The fuel choice is determined by the type of fusion process being considered; for example, deuterium–tritium, deuterium–deuterium, deuterium–helium-3 or proton–boron-11.

## Research, development and demonstration metrics and milestones for commercialization

The following development metrics can be used to assess the progress in fusion energy RD&D:

- Demonstrating high performance and continuous operation (or high repetition rate pulsed operation for inertial confinement and magneto-inertial fusion) while achieving conditions at the plasma–material interface that ensure acceptable lifetime for in-vessel components.
- For D–T based fusion energy concepts:
  - Realizing a tritium breeding ratio[5] larger than one, possibly involving lithium-6 enrichment;
  - Demonstrating efficient tritium extraction and recirculation;
  - Developing the appropriate supply chains for tritium fuel production;
- Showing net energy gain that can be extracted from a fusion plant.

The following essential milestones need to be achieved for commercializing fusion energy:

- Demonstrating simultaneously fuel sufficiency[6] and net energy gain in a single fusion plant;
- Securing the site of the fusion plant and obtaining licences/permissions for construction, operation and decommissioning;
- Establishing appropriate strategy and regulatory pathways for waste management;
- Connecting the fusion plant to an energy consumption system or grid at a competitive price.

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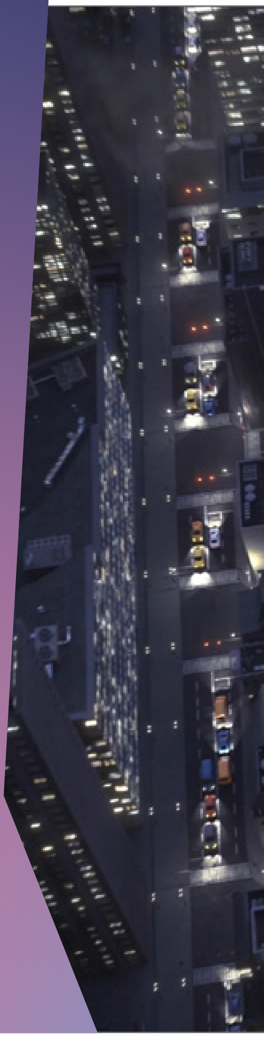
[5] The ratio of the overall tritium production rate to the total consumption rate in a fusion machine.

[6] Self-sufficiency or through external fuel supply.

# 2.

# Resources, workforce and knowledge management for **industrialization**

Establishing a fully fledged industry capable of unlocking the potential of fusion requires adequate resources, creating parallel revenue streams, building a competent workforce, effective knowledge management strategies, and clear legal, regulatory and intellectual property frameworks.



## Financial resources and funding mechanisms

The size of investment, both public and private, as well as the timescales for which the investment effort will need to be sustained cannot be underestimated. This is due to the technical complexity of mastering fusion, the exacting conditions that any energy producing plant will need to maintain, as well as the scale of the scientific and industrial facilities that will be required for research, development, testing, manufacturing and finally energy production.

Photo: Zap Energy

**Public and private resources will play different but complementary roles. Investment from governments will be key in the following ways:**

## Funding research and early development

Fusion energy still requires important RD&D efforts. For the RD&D areas at low TRL, research institutes and similar public organizations play an important role, and the development of an industry will require the continuing funding of such institutions and their programmes. Private organizations, although less engaged in fundamental research, are also important actors in the early development stages and often engage with public support through different mechanisms such as grants, tax breaks and public–private partnerships. Public support and funding to accelerate RD&D are essential, especially at this stage of an emerging industry. However, the actual strategy of this support requires particular care, as excessively cumbersome arrangements (e.g. fragmentation of support mechanisms, size of individual grants, arrangements relating to the created intellectual property, cost accounting, reporting burdens) can make such support mechanisms unattractive to both public and private organizations.

## Funding demonstrator projects

Projects that act as technology demonstrators and/or testing facilities are crucial to establishing and sustaining the industry but might require public funding if they do not constitute commercial assets. Such projects (e.g. **ITER**), can allow the development of a supply chain, as public and private companies compete to participate and thereby develop their competencies and industrial base. The funding of such projects needs to be maintained even when difficulties or delays occur, and these projects need to be of sufficient commercial relevance, duration and number to allow the establishment and sustainment of an industrial supply chain.

**ITER**, currently under construction in France, is the largest fusion experiment under development. The project is a joint international undertaking between China, the European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States of America. The purpose of ITER is to demonstrate the scientific and technological feasibility of fusion energy production.


Photo: ITER Organization

## Supporting pilot plant and/or first of a kind projects

Some national fusion strategies, based on national policies and commercial practices, assume that private — rather than public — entities will lead the demonstration and deployment of commercial fusion plants. To achieve this, governments would need to enable a transition from the public to the private sector using adequate risk sharing mechanisms for early commercial plants (pilot plants and/or first of a kind projects), where the risk–reward balance is such that some governmental support will still be required to allow the private sector to raise the required capital. This can take a number of forms, as demonstrated in other comparably complex industries with projects being led either by the public or the private sector supported through risk sharing mechanisms[7].

**Financing (equity and debt) from private investment can include, but is not limited to, the following aspects:**

→ Development and industrialization of the technology through specific fusion schemes and their associated plants and components;

→ Development of industrial capability in the form of competencies, processes (e.g. manufacturing processes) and tools required for the implementation of such schemes;

→ Development of test facilities (e.g. fuel cycle) and plant projects (e.g. pilot, first of a kind and *n*-th of a kind plants).

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[7] Examples of such risk sharing mechanisms include, but are not limited to, milestone based development programmes, contracts for difference or regulated asset base contracts.

## Workforce

The development of a robust workforce tailored for the commercialization of fusion energy necessitates a comprehensive approach involving both public and private national initiatives, potentially supported by international collaboration and knowledge exchange programmes.

Given the current limited size of the fusion community, a concerted effort is required to attract, educate, train and develop a skilled specialist workforce of scientists, engineers, project managers, operators, technicians and regulators capable of meeting the diverse challenges inherent to fusion technology deployment, with an emphasis on developing a broad workforce beyond the present focus of training future researchers.

Building such a workforce would greatly benefit from the fact that the fusion industry is already attracting talent, competencies and experience from other industries. This could be accelerated through targeted skills conversion programmes. However, the level of competition for top-tier scientific and engineering talents across industries and public research institutions cannot be underestimated.

Emphasis needs to be placed on developing specialists with an industry oriented mindset, broad technical expertise, the ability to bridge technical disciplines and experience across various stages of a project lifecycle. This is to avoid the formation of silos between specialities or between the development, design and implementation phases, as well as to support the industry in meeting the anticipated demands of expansion and commercialization. In addition, given that the operation of fusion plants will require a robust supply chain encompassing both highly specific fusion technologies and elements common to other industries, fostering such cross-disciplinary proficiency is vital.

## Knowledge management

The development of the fusion industry and the commercialization of fusion energy requires the creation and wide dissemination of scientific, engineering, manufacturing and operational knowledge. Today, publicly funded projects constitute a significant part of the development and sharing of such knowledge. Therefore, they need to seek to maximize the creation, documentation and dissemination (under appropriate protocols) of such knowledge. Participation of the public and private sectors in knowledge management and sharing can be facilitated through clear and robust intellectual property frameworks. Industry fora can also play an important role, by promoting the sharing of information essential to aspects such as safety, security and operational excellence to the benefit of all.

As the fusion industry is an emerging industry, as well as one pursuing several different technical approaches, it is also important that knowledge is shared with comparably complex, more established industries, as well as between the projects investigating the different confinement approaches to fusion. To that end, professional bodies, trade organizations and exchange programmes between regulators can play an important role.

Finally, the acquisition and organization of knowledge through national and international norms, codes and standards, and the sharing of guidance and/or best practices can also strongly support the development of the industry.

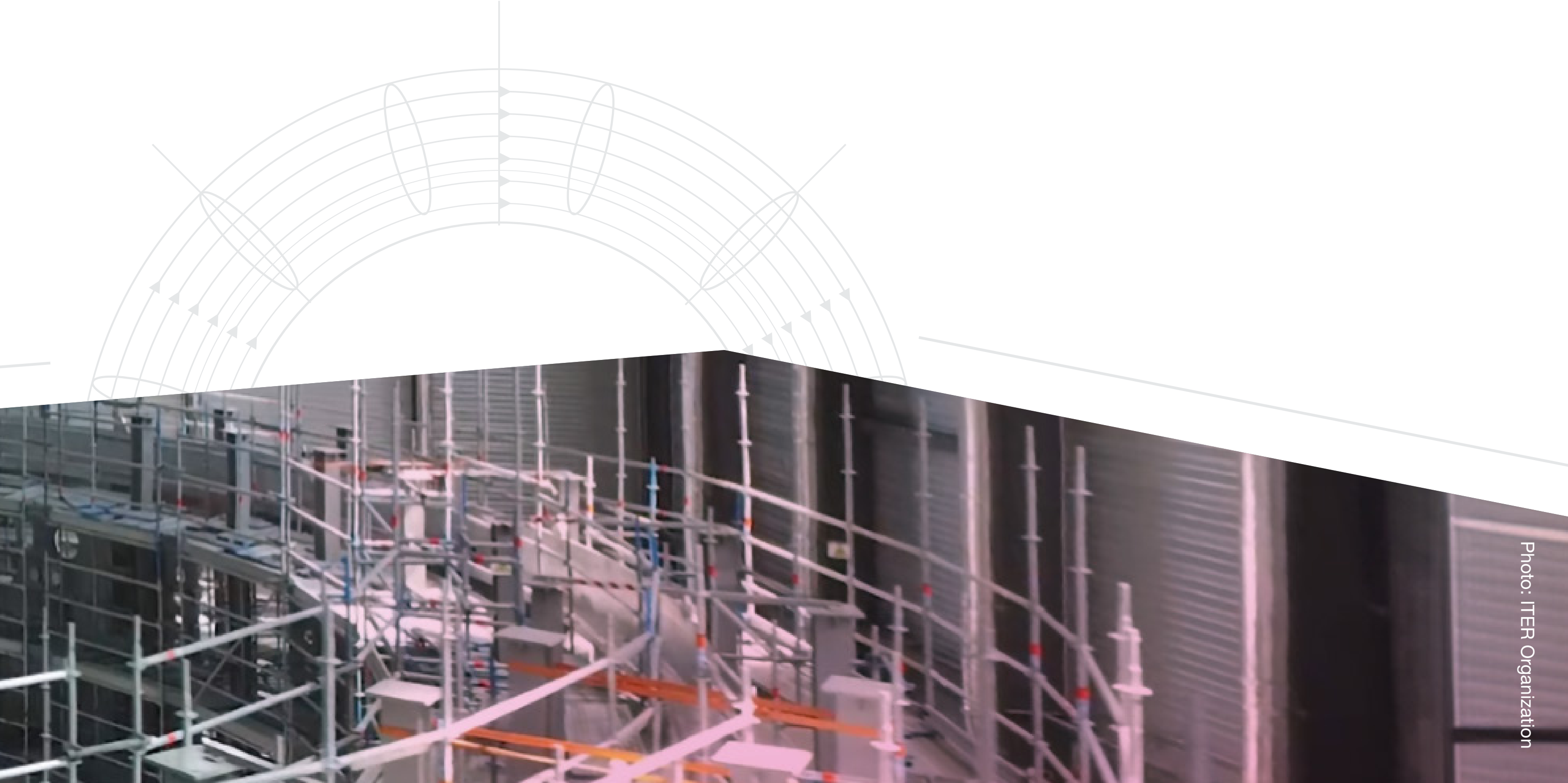

Photo: ITER Organization

## The journey to industrialization ▸▸▸▸▸

Although fusion remains a nascent field, drawing from the evolution of the existing energy sector, it is likely that there will be large integrator companies, second tier enterprises that specialize in systems or subsystems of a fusion plant, and a very large number of small to medium sized enterprises that have specific intellectual property in components or parts. The creation of a vibrant sector will need interventions that enable all these types of company to grow competence and experience in fusion.

The successful transition of fusion technologies from research and early development to commercial applications will be crucial for the establishment of a thriving fusion industry. Traditionally, large scale national and international projects have served as de facto anchor tenancies[8], contributing significantly to maintaining the fusion supply chain and human resources. To further develop the fusion industry, it is necessary for the public sector to continue to play an active role in sustaining the supply chain through its public programmes, including establishing new research facilities, to ensure a seamless transfer of knowledge and expertise accumulated in public programmes to the industry under adequate arrangements. These public programmes will complement the private sector's investments, which could include the activities outlined on p. 17. Additionally, several key enablers will still be required, including the following:

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[8] An anchor tenancy is a long term commitment by a government to provide a stable revenue base and reduce financial risk for private companies.

## A clear and stable legal and regulatory framework

An important part to attracting private funding and developing credible development plans is clarity regarding the legal and regulatory framework, including establishing processes for obtaining permits for siting, construction and operations.

## A robust intellectual property framework

A robust intellectual property framework is essential to facilitating collaboration among parties during the transition from research to commercialization of the technology.

## Technologies relevant to both fusion energy and other markets

One key challenge for the establishment of a private fusion industry is that in view of the timescales associated with its development, investors often require short to medium term revenue streams. Those can come from the application of technologies developed for fusion to other markets (e.g. innovative materials, robotics, medical applications). Development programmes, whether public or private, could be designed to facilitate this.

## A broader ecosystem of collaboration

By creating hubs of capabilities in the field (often regional ones inviting participation by state and local governments and their communities), the creation and sharing of knowledge, as well as the development of technologies, can often be accelerated via a dynamic environment where multiple organizations can collaborate, share development costs, as well as pool expertise and competencies.

# 3.

# Safety, security and non-proliferation

Regulation of safety and security of fusion plants needs to be commensurate with their risks, taking into account their unique features, such as the absence of a chain reaction and their immediate shutdown capabilities. Equally important is ensuring low risk of proliferation by design and through regulatory oversight as fusion energy develops.

## Radiation safety fundamentals

Safe, secure designs are essential for the successful deployment of fusion energy. The safety approach for fusion plants needs to be consistent with IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [2], which applies to all circumstances that give rise to radiation risks, including uses in the medical field, power generation and industry applications. The fundamental objective within this framework is to protect people and the environment from harmful effects of ionizing radiation.

The fundamental safety principles in SF-1 [2] are applicable to all facilities and activities utilized for peaceful purposes, throughout their lifetime, and to protective actions to reduce existing radiation risks. Such facilities and activities include any place where radioactive materials are produced, processed, used, handled, stored or disposed of at such a scale that consideration of protection and safety is required [2]. Therefore, these principles can apply to fusion plants, which both use and produce radioactive materials at a scale that warrants consideration of safety.

IAEA General Safety Requirements Parts 1–7 [3–9] address topics such as safety assessment and regulatory frameworks. The General Safety Requirements are applicable to all uses of radiation, including fusion machines.

The organizations responsible for assessing and controlling radiation risks need to assess and control radiation risks to people and the environment as a result of normal operations and incidents/accidents. This applies throughout the lifecycle of the facility, including design, operation, fuel and waste management, and dismantling/decommissioning. Modelling and diagnostics will be needed to support the safety case. It is essential to consider safety measures from the very beginning of the design process for all involved systems. Owing to the novelty of fusion plants, the uncertainties in the performance of various systems need to be carefully addressed in the safety analysis. Depending on the technology, different material interactions (e.g. lithium, water), radioisotopes and particle energies are expected, resulting in a variety of hazards that need to be considered. Fusion plant designers need to consider these principles to reduce hazards and minimize radioactive waste, where feasible.

## Approaches to regulating fusion energy

Fusion experiments have already been licensed and operated for research and development (R&D) in some IAEA Member States. In coming years, designers are expected to produce the first pilot and demonstration projects. If these projects are successful, they could be followed by widespread commercial adoption of fusion plants.

For the designs being contemplated for widespread commercial adoption, Member States are currently evaluating approaches to regulating fusion plants that are commensurate with their risks. These evaluations take into account the inherent features of fusion (e.g. lack of chain reaction, immediate shutdown on loss of power), the characteristics of the radioactive materials involved and the management of radioactive materials on site. This approach is reflective of the IAEA's graded approach to regulations [10].

Requirements and guidance already exist or are being developed in Member States for fusion plants and the safe management of radioactive waste, consistent with national frameworks and the associated hazards. These requirements and guidance address both safety and security. The IAEA can support regulatory bodies in developing safety requirements and security guidance for fusion energy that are appropriate for the technology and hazards and enable incorporation of lessons learned as designs mature, as has been done in other regulatory regimes.

Cooperation among regulators is advantageous. Common approaches and consistent decision making across Member States, where feasible, will streamline the application process, as designers will have a lesser need to revise their applications, technical solutions and justifications across jurisdictions.

Common terms and common positions on technical matters can aid all regulators, even if different regulatory approaches are applied. Continued regulatory collaboration on emerging technical challenges, as well as security topics such as cybersecurity, can help to share knowledge and experience so that fusion plant regulations address these areas appropriately.

International organizations such as the IAEA can facilitate bilateral and multilateral discussions among Member States developing similar regulatory frameworks. Coordination within the IAEA for consistency and coherence of effort will support all Member States in advancing their fusion regulatory structures. A decision on whether the IAEA needs to develop safety standards for fusion may not be warranted until fusion plants have matured.

Industry standards organizations could have a role in developing common design approaches that can help to streamline regulatory reviews.

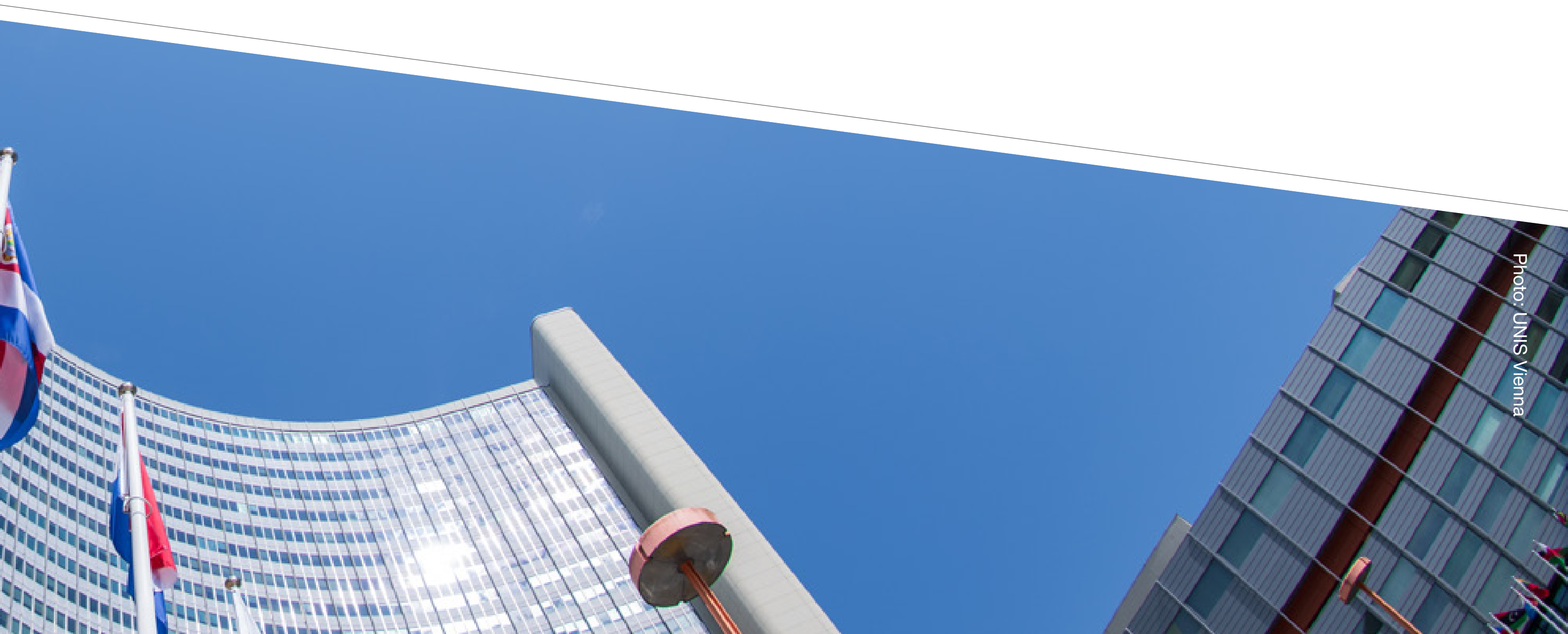

Photo: UNIS Vienna

## Transition to widespread commercialization of fusion plants

To date, experience in fusion energy has been limited to R&D projects. Fusion energy production and commercialization are expected in the future. This will involve construction of fusion plants (prototype, demonstration and/or commercial plants).

As fusion technology develops further, regulatory bodies may adopt processes that are appropriate to the stage of development. For example, the graded approach might be used to specify different licensing requirements and oversight at each stage. Differences driving safety decision making can include higher inventories of radioactive materials; transportation, storage and processing of fuel; waste disposal categories and volumes; and the need for active cooling of some components. Regulators are likely to find that their reviews and processes become more efficient for *n*-th of a kind plants. Specifically, new licensing paradigms might be needed for mass manufacturing and widespread deployment on a rapid timescale.

## Other hazard considerations

The IAEA and many Member State regulators coordinating fusion energy projects focus on radiological safety and security. Fusion plants have additional potential hazards of an industrial and occupational nature, given the high energy in the system and potentially toxic materials. A detailed discussion of these hazards is outside the scope of this publication. However, in communicating with the public, the fusion energy community can discuss how to identify and mitigate these hazards to protect workers and the public.

Photo: ITER Organization

## Non-proliferation considerations

It is important for designers to be mindful of prevailing nuclear export control regimes regarding materials associated with fusion energy, such as tritium and lithium-6, and certain technologies, such as analysis codes.

For fusion designs that do not process, use or produce nuclear material[9], the IAEA does not currently apply any safeguards measures other than those needed to resolve questions, where applicable, relating to the accuracy and completeness of the information provided by Member States. Existing international safeguards agreements apply to designs that process, use or produce nuclear material. As more information about fusion plant designs becomes available, further consideration is required to ascertain whether the scope of IAEA safeguards would apply more broadly to fusion plants.

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[9] IAEA safeguards apply to source material and special fissionable material, as defined in **Article XX of the Statute of the IAEA.**


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# 4.

# Global collaboration

The fusion energy ecosystem is rapidly evolving, driven by international collaboration and increasing private sector engagement. Global cooperation is essential to address the areas requiring further progress, establish international supply chains and develop the skilled workforce necessary for the commercialization of fusion energy.

## The evolving fusion energy ecosystem

The pursuit of fusion energy is inherently international, demanding global cooperation to address the remaining RD&D areas, establish international supply chains and develop a skilled workforce. This global engagement is vital for the commercialization of fusion energy to play a role in sustainable energy transitions.

Over the past sixty years, fusion energy development has advanced through extensive collaborative efforts in fusion science and technology between different nations. The ITER project is the greatest example of this spirit of collaboration. Bridging these foundational collaborative efforts with the industry is a pivotal step towards integrating the burgeoning private sector into the established fusion energy development ecosystem.

National initiatives such as Germany's **Fusion 2040**, Japan's **Fusion Energy Innovation Strategy**, the United Kingdom's **Towards Fusion Energy** strategy and the United States' **Fusion Energy Strategy 2024** exemplify policies that utilize existing infrastructures and foster collaboration among countries, public institutions and private entities, and illustrate successful strategies to unite a diverse array of industry participants with fusion developers. Recent public–private alliances, such as China's **China Fusion Energy Consortium**, Italy's **DTT Consortium** and the United Kingdom's **UK Industrial Fusion Solutions Ltd**, are pioneering the potential of these collaborations.

**Fusion 2040** is a funding programme launched by the Government of Germany for the development of a fusion power plant design.

**Fusion Energy Innovation Strategy** is Japan's first national strategy on fusion energy, which includes the establishment of an industry group (Japan Fusion Energy Council) to accelerate fusion energy development.

**Towards Fusion Energy** is the United Kingdom's fusion strategy for the delivery of fusion energy. It includes a programme for the design, development and construction of the STEP (Spherical Tokamak for Energy Production) prototype fusion power plant, and Fusion Futures, the new R&D programme of the Government of the United Kingdom.

**Fusion Energy Strategy 2024** is the fusion strategy of the United States of America to accelerate the viability of commercial fusion energy in partnership with the private sector. It includes a proposed fusion energy public-private consortium framework.

**China Fusion Energy Consortium** is an industrial alliance established by the Government of China for the development and advancement of fusion technology.

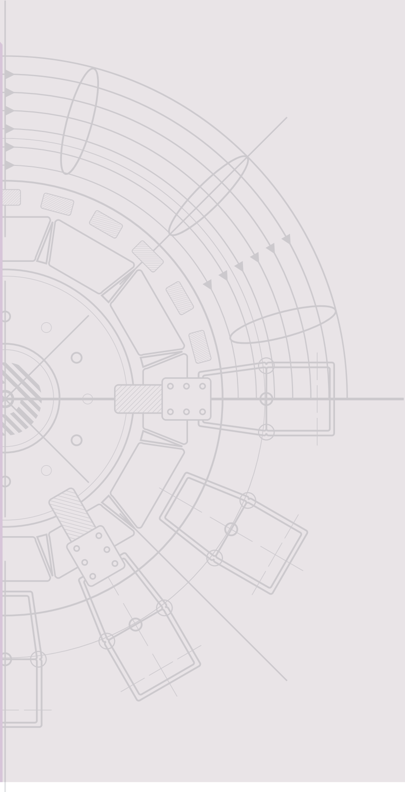
**DTT Consortium** is a public–private alliance for the construction and operation of the DTT (Divertor Tokamak Test) fusion experimental facility.

**UK Industrial Fusion Solutions Ltd** is a public–private alliance to deliver the STEP prototype fusion power plant.

Additionally, public–private partnership models, such as the United States' **Milestone-Based Fusion Development Program** and the **INFUSE** initiative, exemplify effective mechanisms for facilitating the fusion industry's access to technical and financial resources, and further catalyse private investments in fusion, accelerating the journey from basic research to commercial viability. These programmes underscore the importance of collaborative risk taking, milestone achievement and government support in nurturing a dynamic and inclusive fusion energy ecosystem for technology transfer from early stage development to commercial deployment, emphasizing the protection of intellectual property and the diversification of technological approaches.

The **Milestone-Based Fusion Development Program** is the United States Department of Energy's five year programme to advance designs and R&D for private sector-led fusion pilot plants.

**INFUSE** (Innovation Network for Fusion Energy) is an initiative of the United States Department of Energy to provide the fusion industry with access to technical and financial support with the assistance of its funded fusion institutions.



# Leveraging international cooperation and public–private partnerships

## Global collaboration in a healthy competitive environment

International collaboration is integral in sharing knowledge in fusion science and technology, advancing possible development paths and accelerating fusion energy commercialization. Global collaboration can pool expertise and share the cost of RD&D projects, speed up mutual progress by sharing information and knowledge, and help countries to build infrastructure relevant to fusion technologies. The demand for time and resources has proportionately increased with technological complexities in addressing the RD&D gap areas, emphasizing the need for international collaboration to promptly achieve the goal of fusion deployment and commercialization by sharing risk and investment. An example of this aspect is the design, R&D and construction of the ITER project. An ecosystem that promotes healthy competition between the different fusion energy development approaches can allow national and private sector strategies to move in parallel within the context of global collaboration.

## Effective use of capital-intensive facilities

Many nations have established R&D infrastructure for developing fusion energy through national programmes. These include experimental facilities, fuel recovery systems, storage systems, liquid metal loop facilities, and material irradiation, testing and manufacturing facilities. Owing to their capital-intensive nature, establishing test facilities will be prohibitively expensive for nations starting fusion energy programmes. Sharing infrastructures internationally, as well as with the broad private sector fusion industry, can further accelerate deployment of fusion plants and avoid duplication of efforts. By distributing the cost among two or more countries, duplication of infrastructure will not be necessary, and both parties, as well as the international fusion industry, will benefit. Collaboration agreements that are mutually agreed upon can be used to put such arrangements into action.

## Sharing and maintaining databases

It is important for the fusion community to recognize the vital importance of facilitating improved access to scientific data for researchers, policymakers and the public, which will promote transparency and reproducibility and foster international knowledge exchange. Creating a centralized database platform for R&D groups working in fusion science and technology is essential. This platform would also provide all stakeholders access to data in various formats and applications relevant to fusion energy.

## Personnel exchanges, workforce development

International cooperation offers an opportunity to benefit from resource sharing and the intellectual diversity of the fusion community. Nations can accelerate their technological progress by partnering with other nations that have more advanced fusion programmes and experiences, allowing them to improve their domestic programmes. Greater international participation also increases the diversity and talent pool from which scientific leaders of the future emerge. By providing adequate incentives and ensuring effective management of intellectual property rights, personnel exchange programmes between the collaborating parties in specific fusion technology areas will provide exposure to each other’s facilities. For example, these programmes can provide training for personnel to operate the facilities, yielding mutual benefits.

## Design code validation

Design and safety analysis may rely heavily on analytical codes and methods. Design experts in the fusion community can jointly identify the approach that designers need to follow to comply with regulatory requirements. Databases and codes can be exchanged for validation and verification through international collaboration frameworks.

## Regulatory collaboration

Fusion energy technologies will transcend national borders and become globally integrated as they become successful. The adoption and widespread acceptance of fusion energy will benefit from appropriate regulation harmonized internationally and tailored to the risks associated with fusion plants. The enhancement of regulatory controls and regulatory practices can be achieved through global collaboration.

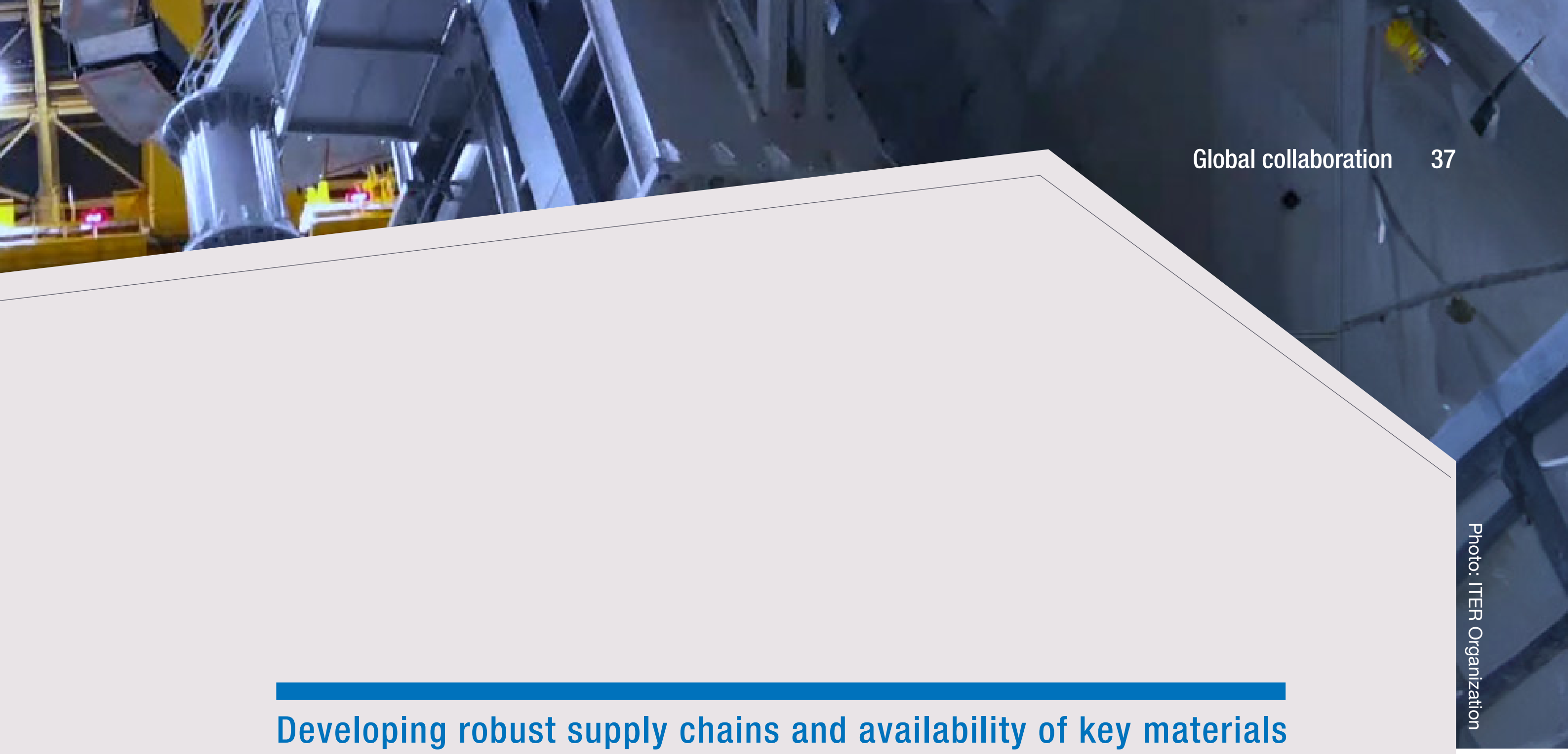


Photo: ITER Organization

## Developing robust supply chains and availability of key materials

The need for key resources (e.g. deuterium, tritium, helium, structural materials, lithium, beryllium, tungsten, copper, silicon carbide composites) for sustainable energy applications worldwide is expected to increase exponentially as the world shifts towards clean energy technologies. There will be vigorous competition globally to acquire resources essential for building and operating fusion plants. The key questions to consider are (a) how can production be increased to meet the growing demand and (b) what are potential sources for the supply of key materials. Collaborative frameworks within the fusion community enable stakeholders to collectively shape R&D priorities across the supply chain. This proactive approach not only fosters innovation but also mitigates the impact of material availability on achieving the fusion community's goals, ensuring a more efficient and sustainable path towards harnessing fusion energy. Strong cooperation within the fusion community is essential to achieve mutually beneficial outcomes and ensure a seamless supply chain of essential materials, thereby keeping energy systems secure and resilient.

# 5.

# Roles of **Stakeholders**

National governments, regulatory bodies, research institutions, academia, private companies, international organizations and non-profit entities need to work in concert to expedite fusion energy adoption and deployment.

## National governments

Considering the substantial resources needed to expedite the demonstration and deployment of fusion plants and the pivotal role that fusion energy could play in a decarbonized energy system, national governments will necessarily be key actors and stakeholders. As such, their involvement is likely to include the following actions:

### Publication of a national policy and roadmap to support the establishment of a fusion industry

National government action needs to be well understood by all stakeholders, aligned across its different delivery bodies and sustained; but above all, it needs to be aimed at a clearly defined overall objective and vision. Countries are developing national policies and roadmaps that outline their goals for fusion energy, specifying targets, timelines and methods. It is crucial for these policies to acknowledge the significant contribution that fusion energy can make to addressing climate change and enhancing energy security, and to address essential enablers, interfaces and dependencies, such as financing and subsidies, to support fusion energy's market entry and competitiveness. These strategies can extend beyond initial deployment, detailing steps toward large scale implementation within a relevant timeframe.

### Definition of the government's role and its expectations for other stakeholders

National governments will make crucial decisions regarding the activities that they will fund or manage through publicly owned entities and those where they will act primarily as enablers or facilitators, expecting the private sector to invest and deliver. The delineation of these roles, the specific activities that they encompass and the expectations and rules for private sector engagement will need to be clearly defined and transparent. These elements will form integral parts of the national policies.

## Establishment of a legal and regulatory framework

A key function of national governments is to promptly establish suitable legal and regulatory frameworks. Equally important is establishing criteria for site selection and obtaining development consent. These frameworks are vital for guiding technology development with the correct priorities, such as safety, security and non-proliferation. They also enable developers to produce reliable early designs and cost estimates, while assuring investors that legal and regulatory risks are well defined, stable and manageable.

## Development of a healthy and facts based national and local discussion

Societal acceptance is important in the development and deployment of new technologies. Therefore, national governments can play a role in public engagement and education, promoting a two-way, open and informed, science based discourse over fusion energy, its role within the national energy system and economy, the size and timescale of the required investment, as well as the benefits that this technology could bring.

## Regulatory bodies

Regulatory bodies are both key actors and stakeholders in the establishment of a fusion industry. They will need to build their own skills and competencies as the technology develops, including through collaboration with industry and research institutes.

Collaboration across national regulatory bodies is also important to ensure sharing of learning across jurisdictions, support the establishment of newer regulators, as well as accelerate harmonization of regulatory approaches. These are all essential elements to the development of an international market of significant size.

## Research institutes and academia

Fundamentally, fusion research activity in the academic sector exists to support discovery. Research institutes and academia (including universities and higher technical education), whether public or private, play a key role by delivering research programmes to increase the TRL and commercialization potential of key enabling technologies to the point where they can be taken forward by the private sector. These activities and, more generally, cooperation with the private sector (such as providing access to research facilities) need to be encouraged and focused on the development of technologies adapted to eventual commercialization. Collaborations between private and public entities need to be supported by a sound framework for knowledge exchange and intellectual property production and protection, as well as a focus on interdisciplinary research programmes.

Research institutes and academia also have a key role to play in the provision of training and development of competencies, either in isolation or through partner development programmes. This will provide retention and renewal of the workforce of the future, and the essential understanding of physics required to realise a fusion plant. Research institutes and academia can also partner through joint programmes with industry and regulators, assisting with workforce development. They can also provide direct technical support to the regulator in the form of up to date competencies, facilities and expertise.

Finally, research institutes and academia can also contribute to the development and acceptance of the industry by society through the field of social sciences.

## Fusion technology vendors

Fusion technology vendors are an important part of the fusion industry's development. These organizations build on research and early development work to create industrial products that can be sold, built, commissioned and operated. As the industry evolves, a diverse range of entities will emerge to take on roles in the design, construction, commissioning and operation of energy producing facilities. At this early stage, it is challenging to delineate the specific responsibilities of technology vendors and other entities.

The emergence of and investment into private fusion technology vendors represent potential market interests that are vitally important to underpin and justify the growing international attention on timely fusion development, demonstration and deployment. To date, there are over 40 such private fusion companies globally, supported by over US $7 billion of investment. These companies are pursuing a wide range of fusion energy technologies in magnetic confinement[10], inertial confinement[11] and magneto-inertial confinement[12]. They are also examining a wide range of fusion fuel choices, including deuterium–tritium, deuterium–deuterium, deuterium–helium-3 and proton–boron-11. Although each specific fusion technology approach has different R&D needs, there are some generally useful R&D areas that could benefit most private fusion technology companies, such as more radiation resistant first wall materials and blanket technology development.

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[10] Magnetic confinement technologies include tokamak, spherical tokamak, stellarator and heliotron, field reversed configuration, magnetic mirror, levitated dipole, cusp and hybrid electrostatic systems.

[11] Inertial confinement technologies include laser and projectile compression systems.

[12] Magneto-inertial confinement technologies include, but are not limited to, liquid compression, field reversed configuration, Z-pinch, plasma jet and magnetized liner inertial fusion systems.

## Supply chains

In addition to fusion technology vendors, the planning, design, construction, commissioning and operation of a fusion plant will require a robust supply chain spanning many domains. While some of these domains are highly specific to fusion, many overlap with other sectors, such as nuclear energy, oil and gas, aerospace and space technology. This overlap introduces a competitive element for skilled workforce and resources, as these industries also demand similar expertise and technological capabilities. Potential actors in the fusion supply chain include key material providers, component manufacturers, plant engineering companies, general construction firms, equipment suppliers, and both specialist and non-specialist service providers. Given the extensive and diverse nature of this supply chain, it is likely to be international in scope.

The competition for workforce is a crucial factor that could impact the development of the fusion industry. As fusion technology increasingly intersects with other high demand sectors, securing and retaining a skilled workforce will be paramount. Addressing this challenge will require strategic workforce planning and collaboration across industries to ensure that fusion energy development does not suffer from a shortage of essential skills and expertise.

Photo: ITER Organization

## International organizations

International organizations play a pivotal role in the development of fusion energy. Their involvement encompasses the following key areas:

- They can support the development of the necessary infrastructure for fusion energy R&D, including research facilities, as well as the future infrastructure needed for commercial fusion plants. These organizations often help to provide essential funding and resources for RD&D projects in fusion energy. Given the high costs and long timelines associated with fusion development, international collaboration can pool resources from multiple countries, making ambitious projects feasible.
- They facilitate collaboration among countries, scientists and researchers, enabling the sharing of knowledge, expertise and research findings. Such collaborative efforts can help to bridge the knowledge gap, accelerate technological advancements and overcome technical challenges more efficiently. Furthermore, enhanced engagement from international organizations in public outreach and education efforts will increase awareness and understanding of fusion energy. This can help to build public support for fusion energy projects.
- They could assist in recommending policies that support the development, deployment and adoption of fusion energy. This can include policies on international cooperation, funding mechanisms and incentives for RD&D.

## Non-profit organizations

Non-profit organizations can serve multiple roles in monitoring public interest and facilitating public discourse as part of the development and deployment of fusion technology.
In addition to general advocacy, non-profit organizations can be key contributors to international, national and local debates on topics such as climate change, energy justice and environmental impacts, as well as provide a voice to groups and communities.

Trade organizations serve a convening role to enable private sector companies to share knowledge in pursuit of setting common standards of performance and, where appropriate, speak as a collective voice to government and regulators on key issues. Trade organizations can also contribute by providing factual, science based and up to date information to key stakeholders, such as government, regulators and the public.

# 6.

## **Public engagement,** outreach and communication

Effectively communicating the potential of fusion energy in providing a long term solution to climate change and energy security is crucial to secure public support for its development.

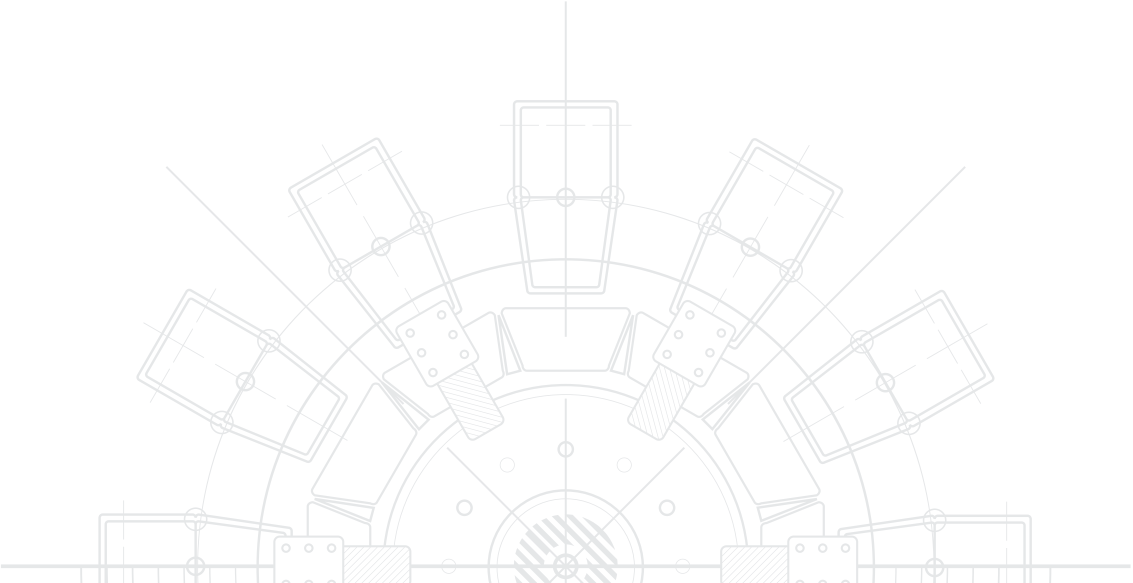
## Effective engagement through two-way communication

Public acceptance of fusion energy is advanced most effectively through two-way engagement. This approach enables designers, governments and others to understand and incorporate local needs, interests and timelines, including input on topics such as energy justice, environmental justice and environmental impacts. In addition, the public can gain an understanding of the radiation risks, the technologies and realistic timelines for deployment. These conversations need to be tailored to the needs and interests of the audience and need to be engaged in with genuine interest by credible experts, including voices from government, industry and regulators. Iterative and two-way conversations enable early adjustments that address public concerns and facilitate social acceptance. Communications that occur at a late stage or that appear to seek only to inform or explain can appear disingenuous if there is no opportunity to incorporate public response.

Much work has been done in recent years to develop the concept of building public acceptance, and even enthusiasm, through such two-way engagements [11–13]. Drawing from such efforts, the fusion community can learn from and apply successful approaches used in other industries, including ‘social licence’ [14], as applied to mines or biomedical technologies; ‘bioethical review’ [15–17], as applied to innovative biomedical technologies; the ‘responsible research and innovation’ approach [18–20], which brings public input to early stage design; and ‘co-design’ methods [21], which bring the public and technologists together to collectively design a technology.

In all these approaches, discussions of fusion energy need to be transparent and objective regarding the progress and timeline for widespread commercial adoption, the potential benefits and challenges, and the resources needed to develop and deploy fusion energy. Benefits of interest to the public include supporting a clean energy transition, economic development and underserved communities, meeting increased energy demand and advancing other fields through the technologies developed through fusion R&D (e.g. materials, magnets, plasma technologies).

Challenges of interest to the public include the management of waste in comparison with other industries and the potential for hazards and off-site releases. It is important to clearly communicate the potential risks that have been identified for both normal operations and possible incidents and accidents, and how they are mitigated to limit or prevent off-site consequences. Transparency and inclusion of emergency planning, where needed, in the public protection measures could provide reassurance and builds public confidence and acceptance. At the same time, care needs to be taken when differentiating fusion from other technologies, as well as when differentiating among fusion technologies. It is important for communicators to avoid inadvertently disparaging any technology and to consider their audience's positions and preferred approaches. Selecting the most appropriate language for the context can avoid unintentional consequences and accurately reflect the stage of development (e.g. experiments, demonstrators, prototypes, commercial plants).



# REFERENCES

[1] FUSION INDUSTRY ASSOCIATION, The Global Fusion Industry in 2024, FIA, Washington, DC (2024), https://www.fusionindustryassociation.org/wp-content/uploads/2024/07/2024-annual-global-fusion-industry-report.pdf

[2] EUROPEAN ATOMIC ENERGY COMMUNITY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, IAEA, Vienna (2006), https://doi.org/10.61092/iaea.hmxn-vw0a

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1 (Rev. 1), IAEA, Vienna (2016).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Leadership and Management for Safety, IAEA Safety Standards Series No. GSR Part 2, IAEA, Vienna (2016), https://doi.org/10.61092/iaea.cq1k-j5z3

[5] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014), https://doi.org/10.61092/iaea.u2pu-60vm

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Facilities and Activities, IAEA Safety Standards Series No. GSR Part 4 (Rev. 1), IAEA, Vienna (2016).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Radioactive Waste, IAEA Safety Standards Series No. GSR Part 5, IAEA, Vienna (2009).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities, IAEA Safety Standards Series No. GSR Part 6, IAEA, Vienna (2014).

[9] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL CIVIL AVIATION ORGANIZATION, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, INTERPOL, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, PREPARATORY COMMISSION FOR THE COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, WORLD METEOROLOGICAL ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSR Part 7, IAEA, Vienna (2015), https://doi.org/10.61092/iaea.3dbe-055p

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of a Graded Approach in Regulating the Safety of Radiation Sources, IAEA-TECDOC-1974, IAEA, Vienna (2021).

[11] HOEDL, S.A., Achieving a social license for fusion energy, Phys. Plasmas **29**(9) (2022) 092506, https://doi.org/10.1063/5.0091054

[12] HOEDL, S. Social acceptance is as important as low costs and net energy production for climate and energy poverty impact, J. Fusion Energ. **42** (2023) 22, https://doi.org/10.1007/s10894-023-00355-x

[13] GUPTA, K., et al. Americans' views of fusion energy: Implications for sustainable public support, Fusion Sci. and Technol. **2024** (2024) 1–17, https://doi.org/10.1080/15361055.2024.2328457

[14] GUNNINGHAM, N., KAGAN, R.A., THORNTON, D., Social license and environmental protection: Why businesses go beyond compliance, Law & Social Inquiry, **29**(2) (2004), 307–341, https://doi.org/10.1111/j.1747-4469.2004.tb00338.x

[15] UNESCO, National Bioethics Committees in Action, UNESCO, Paris (2010), https://unesdoc.unesco.org/ark:/48223/pf0000189548?posInSet=1&queryId=a17553d7-2780-4e51-b9d3-a495cecdab90

[16] NUFFIELD COUNCIL ON BIOETHICS, Novel Techniques for the Prevention of Mitochondrial DNA Disorders: An Ethical Review, Nuffield Council on Bioethics, London (2012).

[17] WARNOCK M., et al., Report of the Committee of Inquiry into Human Fertilisation and Embryology, U.K. Department of Health & Social Security, London (1984), https://www.hfea.gov.uk/media/2608/warnock-report- of-the-committee-of-inquiry-into-human-fertilisation-and-embryology-1984.pdf

[18] STILGOE, J., OWEN, R., MACNAGHTEN, P., Developing a framework for responsible innovation, Res. Policy **42**(9) (2013) 1568–1580, https://doi.org/10.1016/j.respol.2013.05.008

[19] OWEN, R., MACNAGHTEN, P., STILGOE, J., Responsible research and innovation: From science in society to science for society, with society. Sci. Publ. Policy **39**(6) (2012) 751–760, https://doi.org/10.1093/scipol/scs093

[20] BRAND, T., BLOK, V., Responsible innovation in business: a critical reflection on deliberative engagement as a central governance mechanism, J. Responsible Innov. **6**(1) (2019) 4–24, https://doi.org/10.1080/23299460.2019.1575681

[21] SMITH J.M., Extracting Accountability: Engineers and Corporate Social Responsibility, MIT Press, Cambridge, MA (2021).

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