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Challenges in Fusion, from R&D to Education, and Collaboration between Academia and Industry

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This article offers a view of the prospects of nuclear fusion as a sustainable energy source, with a focus on magnetic confinement fusion and tokamaks. It highlights the key theme of integration and presents the EUROfusion programme as a model for coordinated fusion R&D in Europe while stressing the need for public–private partnerships to bridge the gap between laboratory innovation and industrial implementation. A crucial element is human capital development, i.e. the training of a new, diverse generation of scientists, engineers, and technicians. A broader educational effort is called for, with industry–academia collaboration, hands-on training, and mechanisms to retain and transfer knowledge from legacy projects such as JET.

What is Fusion

When light nuclei collide at sufficiently high energy, nuclear fusion occurs. This can happen in an ionized gas, a plasma, at temperatures of tens or hundreds of millions of degrees. The energy released in the process powers stars and can contribute significantly to providing humanity with safe and clean electricity with no greenhouse gas emissions. Understanding and controlling the multi-scale phenomena that characterize fusion plasmas require a multidisciplinary approach, including sophisticated experiments in large-scale devices, numerical simulations, data science, and artificial intelligence for real-time plasma control, as well as advanced diagnostics to track plasma behaviour. The development of fusion power plants will be an industrial endeavour, and will necessitate still more than a decade, calling for both an increasing level of collaboration and partnership between public research and private efforts, and a strengthening of the education and training efforts worldwide.

Recent Developments

A fusion energy record was set using magnetic confinement at the European JET tokamak (69 MJ of energy in a ~5 s plasma discharge, using 0.2 mg of fuel) (EUROfusion 2024), and a positive energy balance was achieved in an inertial fusion plasma capsule (5.2 MJ of fusion energy were obtained at NIF, with 2.2 MJ of energy delivered by the lasers to the target, the highest yield achieved to date) (Lawrence Livermore National Laboratory 2023). The French WEST tokamak kept a stable plasma for over 20 minutes (CEA 2024), and the W7X stellarator reached a plasma energy turnover of over 1 GJ (Grulke *et al.* 2024). The assembly and system commissioning of most ITER components has also significantly progressed in recent years. These achievements have sparked growing interest in fusion, including industries and private investors (Fusion Industry Association 2024). At the same time, there is a rising need for clean electricity to fight climate change and respond to fast-changing social and economic conditions. The war in Ukraine has pushed society to seek energy solutions that don't rely too much on individual countries. Despite heavy investment in renewable energy, which accounts for 12% of electricity production, fossil fuels still make up about 80% of global energy use and about 65% of electricity production (International Energy Agency 2024). Renewable sources need a large geographic footprint, and their intermittent nature, namely for Photovoltaics and wind, requires expensive and environmentally impactful large-scale storage. Therefore, they cannot be the only solution for carbon-free electricity production. Base-load power plants, such as nuclear, will remain important.

Open Gaps

Although many of the fundamentals of fusion energy science are now well understood, there are still gaps in our knowledge. We focus here on magnetic fusion, which in our opinion is the most advanced approach towards a possible power plant. And on tokamaks, which represent the option with the highest Technology Readiness Level (TRL) at present, although stellarators must be looked at as a potential alternative for the prototype power plant step. In tokamaks, we were able to produce record fusion powers and energies in a single plasma 'discharge', in conditions that are akin to those that we foresee for fusion power plants.

In our subjective view, the most important areas for the development of plasma physics for a fusion power plant are the development and control of integrated plasma scenarios over macroscopic times (hours), i.e. ways to achieve and maintain in a stable and high performance state the plasma that forms the core of the fusion reactor, the taming of transient events, an efficient and steady plasma exhaust, and the full capability of controlling the burning plasma regime, i.e. the situation in which the plasma self-heating is dominant over external sources.

Magnetic fusion technology must be cutting-edge in a wide range of fields, from remote handling to cryogenics, plant equilibrium, and high-power microwave sources, to name a few. While all these aspects present significant challenges, the most urgent research and development efforts are probably needed for the blanket – the system surrounding the plasma acting as a neutron shield, ensuring fuel reproduction and energy extraction – which currently has no definitive design, and for the qualifying of materials under the irradiation conditions of the reactor. Special attention must also be given to superconducting magnets, which have a crucial impact on the overall design and costs, and, even more importantly, to licensing procedures. If not addressed early enough in the process of the design of the power plant, these could become an almost insurmountable obstacle.

However, we should not forget that the key word in fusion, in view of the development of power plants, is *integration*. The most formidable challenge on the way to fusion energy does not derive from any one of the science or technology issues, but rather from their integration into a reliable, available, long-lived, and economically competitive power plant. Only programmes that identify and practise this integration, either as they have critical mass on their own, or, more effectively, as they work in tight and open collaborations, will eventually lead to significant progress (Fasoli 2023) and will reach the ultimate goal, fusion power plants.

The European Programme

An example of such an integrated approach is provided by the European programme, especially if it will be able to strike a balance between established knowledge and innovation, and to explore higher-risk, higher-potential solutions compared with those pursued so far. By 'European programme', we mean the one that is coordinated and implemented by the EUROfusion Consortium, supported by the European Commission, even though this is complemented by several European fusion startups, members of the European Fusion Association, which are also investigating gaps in the technology and in the supply chain. The recent important aspect of the involvement of industries in public–private partnerships will make the design and construction phases of DEMO more efficient. By DEMO we refer to a first of a kind demonstration fusion reactor. DEMO must be built using industrial practices, from design to assembly.

Following the footsteps of previous structures for joint efforts in fusion across Europe, ten years ago, fusion research bodies from European Union member states and Switzerland signed an agreement to further cement European collaboration on fusion research, giving rise to EUROfusion, the European Consortium for the Development of Fusion Energy. Currently, EUROfusion supports and coordinates

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fusion research and development (R&D) activities on behalf of the European Commission's Euratom programme within 26 EU member states, while Switzerland, Norway and the United Kingdom participate in the activities with their national fusion budgets. The EUROfusion Consortium has 28 members, three associate partners and about 167 affiliated entities, including over 100 universities, but also a certain number of industrial partners, associated via their respective national representatives.

General Challenges in Fusion Policy

It is obvious that innovation must be present at all levels in a forward looking, transgenerational programme like that of fusion energy – that is, innovation in science and in fusion enabling technologies, embracing state-of-the-art approaches such as Artificial Intelligence, or additive manufacturing. All promising avenues must be explored, with the utmost degree of diversity – *diversity* intended in all meanings of the word, including that of the background and vision of the individuals contributing to the projects.

In terms of research and development, the European fusion community aims at strengthening its support to ITER while moving as fast as possible towards the prototype fusion power plant, i.e. transforming the lessons learned from ITER step-by-step into the DEMO development programme. This vision was spelled out in the European Roadmap to fusion energy a few years ago (EUROfusion 2022) and has been updated and debated regularly in many public events, policy and scientific documents. In the rest of this article, we comment instead on two elements that are less directly related to R&D but that in our view are also extremely important for fusion developments:

- How to combine industrial and entrepreneurial approaches with the know-how, experience and the ambitious vision of public-funded European fusion programmes.
- How to further develop and retain a unique and diverse human capital.

Partnership between Academic/Public Research and Private Industries

The design and construction of a fusion demonstration power plant, which we refer to as DEMO, require close collaboration between industry and laboratories. The unique, cutting-edge research conducted by laboratories must be transferred into industrial processes. Innovative components, such as the superconducting cables in a conduit conductor (CICC) are often designed, developed and tested at specialized laboratories before the final design is transferred to industry for manufacturing and qualification. Manufacturing at scales required for the fusion industry, however, relies even more on partnership with industry. To avoid the need for geological storage, structural steels with reduced activation (e.g. RAFM, Reduced Activation Ferritic Martensitic steel) were originally developed by laboratories. Industrial

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batches up to weights of the order of tons were produced, and different samples were distributed to metallurgical laboratories for measuring thermo-mechanical properties under irradiation. For the series production of thousands of tons needed in future power plants, an economical metallurgical industrial technology will need to be developed. For example, the Academic Institutions-Industry consortium NEURONE announced the production of 5.5 tons and considered laying the foundation for cost-effective manufacturing of these types of fusion steel for future commercial fusion programmes (UK Atomic Energy Authority 2025).

An approach in which all participating industries are considered only as suppliers does not allow the build-up of scientific and technological competencies in industry, and of the necessary production capabilities. The stop-and-go nature of the contracts does not ensure the retention of experience. Until recently, the time between new large-scale projects did not allow industry to continue to develop innovative projects or to maintain the leading edge it had gained through contracts with research laboratory. The examples of the CICC and of the production of RAFM mentioned above also show that industry needs a long lead time to produce and adapt its production to the fusion needs.

Naturally, industry has expertise in fields that are not fully mastered by research laboratories, such as the integration of complex structures, specialized metrology, brazing and welding technologies, management of large projects. Nuclear industry is familiar with the process of safety certification. A fusion reactor will have to undergo the same complex certification process. The fusion community should already start this process during the design phase of DEMO. Collaboration with the corresponding nuclear industry will avoid technical mistakes and save time. On the other hand, industry may lack the necessary know-how and equipment to bring to the highest technology readiness level (TRL) the innovation that has been developed using public funds. For example, in the case of superconducting cables, testing devices allowing us to measure properties such as the critical current at operating magnetic field under flow of liquid helium at critical conditions exist only in very few research institutions in the world. Similarly, in the field of material, many specialized testing apparatuses have been developed, especially for use with highly irradiated material.

The benefits of having a more structural link between research institutes funded by public funds and industry include a long-term vision of the needs of fusion, which allow the joint development of industrial strategy and the exchange of knowledge and know-how, which in turn will lead to the product meeting both the requirement of a fusion reactor and being suited to industrial production. An R&D focused consortium such as EUROfusion cannot retain sole ownership of the DEMO project after the end of the conceptual design phase.

The capture and transfer of tacit knowledge and of decade-long experience of our fusion experts is also vital to further fusion R&D and support new academic or commercial builds. More emphasis is required to adequately capture and transfer design decisions, lessons learned and best practices in design, commissioning and operation of fusion devices. Projects such as the *ITER Engineering Design*

Handbook, a collaboration between ITER and EUROfusion to capture the design decisions and specifications of ITER as the first experimental burning plasma reactor, are vital. This handbook can act as a crucial reference for the generations of engineers who will design commercial fusion reactors in the future.

Communities of practice around key plant systems need to be developed to share experience and know-how on their commissioning, operation and maintenance. These communities improve not only their operational reliability and performance but also reduce delays due to operational faults and support operator training. This is particularly important in the first commissioning of large-scale fusion projects, where delays can last several years, causing reputation damage as much as significant additional costs.

An important example is the European ECRH network, a community of practice, which was established in 2023 on one of the key heating systems by EUROfusion and Fusion for Energy. It has already created strong bonds between the European teams, ITER, and their international collaborators. Key elements of this network are online seminars, workshops and the first European operator training course to jointly tackle commissioning of new ECRH gyrotrons, train technical staff and advise on the design of systems for future devices. This success underlines a paradigm shift from considering operation as local responsibility with limited interaction between teams to the concept of building communities with joint operator training courses, textbook(s), publications and a mobility scheme similar to that of physics exploitation.

Extension of such communities of practice to industry could further facilitate knowledge transfer. In fact, the evolution from experimental devices such as ITER into commercially viable fusion power plants will require a single integrated plasma scenario to be run repeatedly with limited diagnostics and actuators at a significantly higher plant availability, reliability and low maintenance periods. Transitioning to long pulse operation of the order of hours with limited downtime requires close collaboration with industry to improve and certify plant components suitable for power plant use.

The case of heating systems, such as gyrotron microwave sources for ECRH, is particularly instructive. In parallel with the need to extend manufacturing capability lies the need of R&D efforts to sustain high performance over minutes/hours, as well as sharing experience of commissioning and operating such systems to ensure reliability, availability and adequate performance. Close collaboration in Europe with the manufacturer Thales, and their involvement in the operator training of the European ECRH community facilities provide an example of this type of a relationship, in which crucial lessons-learned and best practices can be integrated in the design phase of systems for future devices and can help reduce potential delays in commissioning.

Industry would have the advantage of being able to retain experience by offering a long-term perspective for the innovative R&D, leading to innovative products for markets beyond fusion. Starting now, such a process will allow fusion to have, by the time of construction of DEMO, a full supply chain for power plants. To establish a working supply chain requires time. For example, in the field of Small Modular Reactors (SMR) key industrial players are starting now to engage in the establishment of a complete supply chain (Nuklearforum Schweiz 2024). Both partners will access specialized test stands, which may alleviate the cost of R&D to bring a product to the TRL level needed for industrial production.

To ensure the industrialization of fusion, DEMO should and will be designed and built within a fully industrial framework. It is thus essential to combine industrial and entrepreneurial approaches with extensive know-how, and the ambitious yet realistic vision of a public-funded European fusion programme. We need a collaborative approach involving joint leadership between research institutions and industrial partners, a combination of strategic alliances, public and private intellectual property, agile procurement processes preserving the public procurement rules. That is, we need Public-Private-Partnerships (PPP): according to the Fusion Industry Association (2024), PPP agreements were signed between 16 Private companies developing fusion and cost sharing with government. The synergy between research institutions and industries is a must for the successful development of fusion.

Innovation, industrial view and strategic partnerships – therefore PPPs and all possible mechanisms combining research and industrial developments – are also urgently needed to address technological gaps prior to DEMO design. These include breeding blankets, structural materials that resist unprecedented mechanical and thermal loads, such as tungsten (Coenen *et al.* 2023; Riesch *et al.* 2024), and superconducting magnets that generate large magnetic fields in very large volumes – just to name a few examples. These PPP would also be the vehicle to develop capability and capacity in supply chains for DEMO and fusion power plants deployment, especially in areas that are not stimulated by the ITER procurement.

The synergy between research institutions and industries is a must for the successful development of fusion power plants, an important building block for a sustainable future for our planet.

Human Capital

The development of fusion is driven by many institutions, but, more importantly, many human beings, with a wide and deep spectrum of competencies. The new generation of scientists, engineers and operators are the lifeblood of the trans-generational fusion effort, both for research and for industrial developments. As private investment and industry involvement in fusion grows, so does the need for a highly skilled workforce. For example, Commonwealth Fusion System has hired about a thousand professionals over the course of the past decade. European universities, laboratories and companies must educate and train university students, and provide vocational training for technical staff as well as onboard professionals transitioning into fusion from other sectors for both the public and private sector.

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Despite the steady increase in the number of university courses and degree programmes focusing on fusion, there is still a significant gap in the availability and accessibility of introductory and advanced courses across European universities and countries (Belonohy *et al.* 2024). As fusion research is a multidisciplinary effort, it requires experts in diverse disciplines in physics, engineering, information technology, mathematics, chemistry and more. Thus, universities and research centres must work together to build a comprehensive curriculum aligned with active research areas and integrating recent developments.

A new initiative to be launched in 2025 in Europe has been designed to achieve this. The Fusion Education and Learning Hub, EUROfusion's e-learning site, will host recorded and live online university courses across multiple universities, disciplines and research areas to create and offer free access to a comprehensive fusion curriculum for students, new and current staff, or people interested in fusion research in a joint effort. It will further work with research groups to develop training material in cutting edge, scarce and important research areas.

This open approach to fusion education can have benefits beyond training current students. It can raise awareness of fusion challenges, showing their cutting-edge nature, and of the potential of fusion for sustainable energy production. It can also enhance the attractiveness of career paths in fusion for high-quality diverse individuals at different stages of their professional careers. This applies to new staff and as well as to current staff, who should be offered continuous education opportunities in the wide fusion disciplines.

It is also important to note that plasmas are used beyond fusion in various fields, including space propulsion, microwave technologies, pollution reduction for cargo ships, sterilization, dermatology, oncology, dentistry, and innovative particle acceleration methods for high-energy physics. A dynamic workforce that moves across disciplines and industries fosters innovations contributing to enhanced technology and knowledge transfer. EIROforum, a collaboration among Europe's leading research centres – including CERN, EUROfusion, ESO, ESA, and EMBL – demonstrates this by sharing expertise and best practices across multiple scientific domains.

Yet, for fusion developments to change gear, more needs to be done. Universities must be supported in hiring new lecturers, creating university fusion groups and developing new courses, degree programmes to establish, expand and strengthen fusion education in more countries and universities. Programmes such as the UK's FOSTER (Walkden *et al.* 2024) and the Candu Owners Group's Train the Trainer can facilitate the integration of researchers into academic institutions as guest lecturers, sharing their expertise in niche emerging areas. Courses and initiatives at Bachelor level, where students choose their master's degree direction and thesis, are scarce. Hackathons, internships and summer/winter schools often offered for Master and PhD students (Cruz *et al.* 2024) only, can provide opportunities for these students to hear about fusion and get excited about fusion as a career path.

Gaining hands-on experience on small, medium-sized experimental or teaching facilities at an early career stage equips students with transferable skills, preparing them for large-scale fusion devices, where training can take years due to exponentially increasing engineering and operational complexity.

Interest in operator training is growing, particularly for heating systems and physics pilots, who oversee plasma discharge development and act as a bridge between scientific teams and engineering operators. The latter takes 4–5 years to train for and strongly benefits from experience on smaller devices. Equally critical is vocational training for technical staff, whose numbers have halved in the last decade, despite their essential role in manufacturing, assembly, and commissioning.

Finally, strong emphasis must be placed on training engineers in scarce, emerging, and high-demand areas, ensuring continuity of know-how from (retiring) experts and their mobility between research groups and the industry. Retaining expertise from JET remains critical, given its unique role as the largest fusion device with tritium-handling capabilities. With over 40 years of operation, JET has accumulated invaluable experience – in engineering operations as much as management – which should be safeguarded and leveraged for future large-scale fusion projects.

Competitive job markets, short-term funding, and lower academic salaries hinder staff retention and recruitment in the public sector, in many, if not most, European countries. While industry partnerships can offer new opportunities, a robust academic R&D environment remains essential for education and further technological innovations in fusion.

Ultimately, we must attract and train high quality and diverse individuals – diverse in all senses of the word – as the new generation that starts today in fusion will be the one that, by operating in the context of public–private partnerships, will lead to our ultimate goal, fusion power plants.

These exciting developments and cutting-edge topics addressed by the fusion programme – integrating plasma physics with energy technologies and the ones needed by industry in general – represent a unique force of attraction and provide an optimal environment for training new generations of scientists and engineers. This is a crucial resource for the success of the global and intergenerational challenge that fusion energy research represents.

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