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PROGRESS IN FUSION WORKFORCE DEVELOPMENT AND EDUCATION IN EUROPE, USA, JAPAN AND ITER

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Abstract

The fusion energy sector is experiencing significant growth driven by substantial private investment, widespread industry involvement, and scientific breakthroughs that demand a highly skilled workforce. Meeting these needs requires coordinated strategies and a multi-faceted approach encompassing expanding academic programs, vocational training, and robust knowledge preservation pathways. The paper describes recent initiatives and strategies developed in Europe, the USA, Japan and at ITER emphasizing the importance of a coordinated effort to attract, train and retain fusion scientists, engineers and operators across career stages. Early STEM engagement, higher education, postgraduate training and knowledge management can strengthen the fusion workforce by ensuring that expertise, knowledge retention, and engineering capacity keep pace with the evolving demands of fusion research and technology deployment.

1. INTRODUCTION

Scientific breakthroughs and energy records in both magnetic [1] and inertial [2] fusion have intensified interest in the fusion sector resulting in significant private investment and widespread industry involvement in recent years. Addressing the need for a highly skilled workforce supporting this growth requires a multi-faceted approach that includes expanding academic programs, developing vocational training, and strengthening knowledge retention mechanisms. Workforce development strategies were developed in the USA, UK and Europe [3-5] in 2024 to attract, train, and retain fusion professionals along with a new set of dedicated activities to enhance fusion education locally and worldwide also launched in Japan, and by ITER and IAEA.

2. EARLY ENGAGEMENT

The expansion of public engagement, particularly in early STEM education, plays a critical role in inspiring and attracting the next generation of fusion scientists and engineers. UKAEA strengthened its engagement of students from primary school, secondary school, and universities using classroom visits, shows and workshops, work experiences, and structured internships. In the USA, new university partnerships and national STEM programs introduce students to fusion early. The Fusion Energy Week organised by the US Fusion Outreach Team has been expanded to Europe in 2025 offering dedicated outreach activities, seminars and visits to facilities in the USA and several European countries (UK, France, Switzerland, Netherlands and Luxembourg).

There are increasing number of initiatives - among others – by FuseNet [7], UKAEA and ITER, engaging secondary school teachers directly through dedicated events and visits, while offering a repository of educational materials, books, seminars. For example, the ITER visit for secondary school teachers organised by the European Commission [6] has seen a participation of over 260 European teachers with an estimated reach of 9700 students since the start of the programme in 2023. The programme offers a visit of the ITER Cadarache site, including the Assembly Hall and Tokamak Pit, presentations on ITER physics and engineering challenges and classroom-ready fusion teaching materials. In an interactive workshop, the teachers further exchange ideas on how to bring fusion to the classrooms. Classroom teaching material and guides are also available from FuseNet translated into 8 European languages.

3. HIGHER EDUCATION

Strengthening fusion education requires attracting STEM students at undergraduate and graduate levels while addressing the faculty shortage and key gaps in access and curriculum. The university education system has to train professionals for both academic research as much as for the increasing number of private companies and industries involved in the fusion ecosystem. In Europe the annual education report provides detailed information on the Master and PhD students, as well identifying the fusion-specific degree programmes and courses at universities [4]. There are currently already 13 dedicated degree programmes focusing on nuclear fusion in Europe in 7 countries (Czechia, France, Greece, Netherlands, Spain, Sweden and the UK). The Joint European ERASMUS-MUNDUS Fusion Master's degree is a joint European programme funded by the European Commission involving 8 universities in Belgium, Czechia, France, Germany and Spain, offering students the opportunity to study in multiple countries, participate in joint training courses and internships in additional 22 global partners in the USA, China, India or at ITER. The USA recently conducted a similar analysis of the fusion courses offered by local universities [8]. While the number of courses indeed increased over the years, in many countries and regions in Europe, fusion education is still limited or absent at the university level (Figure 1).

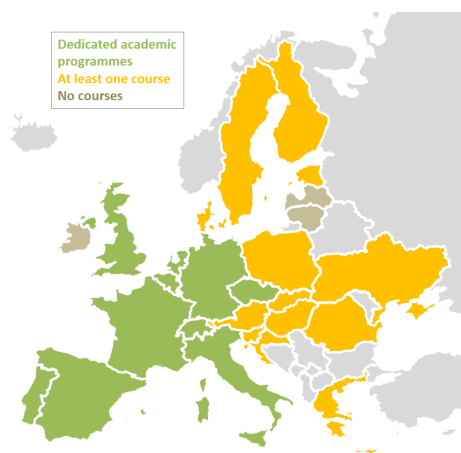


FIG. 1. Availability of academic programmes and courses in Europe

To address accessibility and availability of courses, EUROfusion is launching the Fusion Education and Learning Hub (FuEL) [4] in 2025 that will help bridge the gap by providing open access to recorded and live university courses, along with training materials. The new eLearning platform is built on the open-source Moodle tool and offers information on educational opportunities, universities along with the recorded university courses. Furthermore, understanding and controlling fusion plasmas require a multi-disciplinary understanding from experiments in small to large-scale fusion devices, advanced diagnostics, numerical simulations to innovative engineering solutions. To address this, FuEL collects courses accredited by different universities, with the objective is to create a comprehensive multi-disciplinary curriculum covering physics, engineering, chemistry to operation of fusion devices.

It is equally important to support the recruitment of new university lecturers, development of new courses, degree programmes and creating new university fusion groups. Similar to the Candu Owner's Group Train the

Trainer programme, the UK's FOSTER [5] program is supporting universities by providing visiting lecturers from the UKAEA institutes. In addition to increasing the number of lecturers, this also make the courses closely aligned with current research activities ensuring the latest understanding of cutting-edge research and technologies.

Courses at Bachelor level, where students choose their specialisation are however scarce. In order to combat this, the UK has committed to an ambitious undergraduate research programme to deliver fusion and associated career presentation to 70% of the over 100 UK universities with relevant engineering or physics courses at an undergraduate level. FuseNet's Fusion Hackathon launched in 2025 also targets Bachelor students to introduce them to fusion research and encourage them to specialize in fusion for their Master's degree programme.

Supplementing university education, multinational collaborations, like the ITER International School and the JT-60SA International Fusion School, offer specialised education in key engineering and operational topics. Summer programs in the USA, such as those at PPPL, MIT, and William & Mary, have generated some open-source instructional materials in fusion energy and plasma topics. However, the lack of sufficient in-depth academic fusion courses remains a significant challenge.

More and more experienced engineering professionals are joining the fusion industry from other industries. Accessibility of fusion education is further important for these professionals transitioning into the fusion ecosystem at later stages of their careers, for the fusion industry and private fusion companies, start-ups. The Fusion Education and Learning Hub can offer educational material for professionals, however, does not provide direct interaction with lecturers. The Fusion Industry School, now in its 4th edition and over 200 students is organised by the Fusion Power Centre for Doctoral Training and UKAEA. It delivers a two-part fusion training programme targeted for industry professionals and supply chain organisation. 1-week interactive lectures in York, followed by a week in Oxford, United Kingdom provide an overview of current progress and challenges in fusion. The lectures are further complemented by networking sessions, panel discussions and Q&As with visits to the UKAEA national fusion facilities.

To develop a joint nuclear skills strategy, the European Commission further launched a dedicated Consortium called Skills4Nuclear in 2025 to address the skills shortages and support workforce development in the European Union jointly for nuclear fission and fusion. This project reaches out to industry, private companies, training organisations as well as research to set up a long-term industry-driven collaborative framework to develop nuclear skills for a wide range of nuclear applications.

4. POST-GRADUATE AND VOCATIONAL TRAINING

Post-graduate training programmes, internships and vocational training is critical to train young professionals in these areas. Internship programmes are widely available in the USA, UK, and in Europe where FuseNet and ITER play a vital role attracting and training students and early career professionals. Longer, excellence-based scholarships, such as the EUROfusion Engineering and Researcher Grants, offer post-graduate training in areas identified annually as high-priority to the field. A list of scarce and important post-graduate projects are collated based on feedback from the European institutions, Fusion for Energy and ITER providing an excellent project list for PhD students and post-graduate engineers to find employment following their Masters degree.

Graduate and apprenticeship schemes are increasing, like those in the UK, offering hands-on technical training, and preparing engineers and technicians across diverse fusion-related disciplines. Apprenticeship programs for fusion technicians are available at national labs in the USA, such as PPPL. Vocational training however, while growing, is less widespread and will require further resources to establish.

Beyond graduate physicists and engineers, fusion needs a broad range of professionals, such as administration, human resources, communications, finances and project management. The UKAEA apprenticeship programme trains approximately 40 apprentices each year, providing not only technical education but also opportunities to develop communication, teamwork, and other transferable skills, with structured support

throughout their career journey. Underpinning this effort is the Oxfordshire Advanced Skills (OAS) centre, a dedicated training facility established at UKAEA's Culham Campus. Supported by UKAEA and the Science and Technology Facilities Council and operated by the Manufacturing Technology Centre (MTC), OAS has been delivering workshop-based and core technical training for the past five years. It serves apprentices from UKAEA as well as from a wide range of local employers, thereby strengthening both the regional and national skills pipeline.

5. KNOWLEDGE MANAGEMENT

The preservation and transfer of critical, tacit knowledge is vital in ensuring retaining generational know-how and experience from existing devices while training the next generation of fusion scientists, engineers and operators. Tacit knowledge (table 1), that encompasses the experience and skills gained over time, is particularly difficult to transfer or document.

TABLE 1. KNOWLEDGE LEVELS

Knowledge type	Examples
Explicit knowledge (documented information)	Manuals, notes, videos, documents, how-to guides, databases, memos and historical records
Implicit knowledge (applied information)	Generalized rules, shadowing, practice, logic, beliefs, theorems
Tacit knowledge (information that is understood)	Observation, experience, insights, expertise, education, cultural legacy, organisational values

Following a review of knowledge management (KM) approaches and frameworks, EUROfusion has developed its Fusion Knowledge Management Framework and Strategy [9] in 2023. It is inspired by NASA's knowledge Reapplication Model [10] stressing the importance of communities in the transfer process. It identified four pillars of knowledge management: capturing knowledge in writing, expert-to-expert transfer through communities, education and training, and digital tools for accessibility as shown in Figure 2.

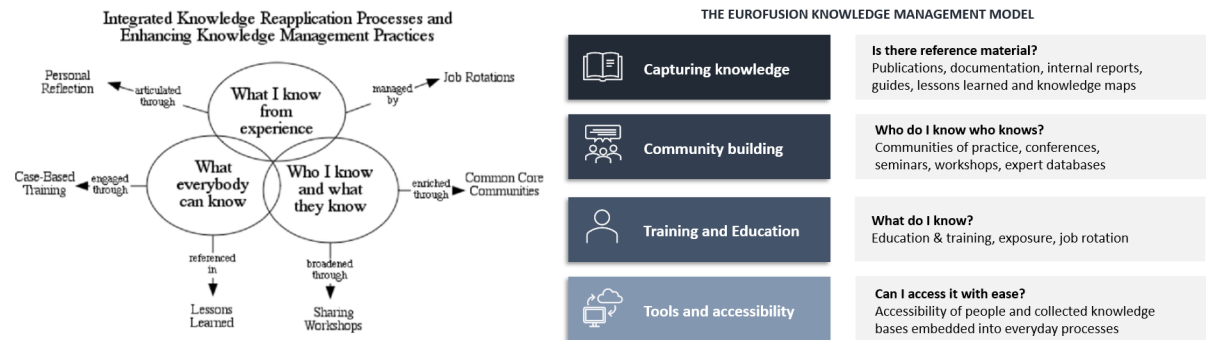


FIG. 2. (left) NASA Knowledge Reapplication Framework, (right) EUROfusion Knowledge Management Framework.

The 2024 EUROfusion Knowledge Management Implementation Plan identified 3 key projects to focus on while implementing the 25 concrete recommendations of the Knowledge Management Strategy into the EUROfusion work packages and processes. The three projects included the ITER Engineering Design Handbook, the extension of the EUROfusion Operations Network and the Fusion Education and Learning Hub (FuEL). In addition, dedicated knowledge management workshops were held with the EUROfusion institutes (197 institutes and universities affiliated to EUROfusion), Fusion for Energy, ITER, EUROforum members (CERN, ESO, ESA, EMBL, European XFEL, ESRF and EUROfusion) as well as guests such as IAEA and NASA.

- EIROforum Knowledge Management Workshop, 4-7 June 2024 (<https://indico.euro-fusion.org/e/EIROforumKnowledgeManagementWorkshop>). Knowledge management approaches from CERN, EUROfusion, IAEA, ESA, ESO, EMBL and NASA.
- EUROfusion – Fusion for Energy Knowledge Management Workshop on Fusion, 12-14 November 2024 (CITE: <https://indico.euro-fusion.org/e/FusionKnowledgeManagementWorkshop>).
- EUROfusion-F4E Knowledge Management Workshop on Technical Documentation, 26 March 2025 (CITE: <https://indico.euro-fusion.org/e/KMseminaronTechnicalDocumenation>);
- EUROfusion – F4E Knowledge Management Workshop on Maintenance (of Old Equipment), November 2025

5.1. The ITER Engineering Design Handbook

The ITER Engineering Design Handbook, launched in 2024 by ITER with the support of EUROfusion, documents and explains design decisions, lessons learned, and insights directly from engineers who designed ITER. The 3-year EUROfusion project (2024-26) will deliver two textbooks with input from over 70 authors from EUROfusion, ITER and ITER domestic agencies with a strong focus to capture:

- Project genesis detailing the influential factors;
- Development of project management principles and tools;
- Rationale in the selection of the main design parameters and in the design space exploration;
- How the physics requirements drove the engineering requirements;
- Lessons learned on what was done correctly and what went wrong;
- Safety and radiological confinement strategy, and the licensing process ;
- Description of system & component design with their interfaces, systems engineering and configuration management;
- Considerations during the preparation and execution of the complex machine assembly;

In addition to facilitating accessibility and understanding of the ITER's technological journey both for stakeholders involved in ITER today and the wider fusion community by consolidating the information from a multitude of (mostly restricted access) sources, the project also put strong emphasis on training the next generation of engineers. The chapters will be reviewed by a group of early career engineers with dedicated training sessions to discuss with and learn directly from the authors, i.e. (retired) engineers who design and built ITER.

5.2. Operations Networks

Communities of practice allow sharing tacit knowledge, share experience and know-how directly between professionals. This is particularly relevant in operation of fusion devices as lot of the knowledge is not written down. The network formed through the communities can support operational teams, and thus operational reliability and performance while also reducing delays due to operational faults and support operator training.

The EUROfusion Operations Network started in 2021 to connect operations teams from European devices, JT-60SA (under the Broader Approach Agreement) with F4E and ITER. Two subnetworks that were launched focused on NBI and ECRH communities of practice. In 2024, EUROfusion started supporting operator training such as Session Leaders at the WEST tokamak and in 2025, launched its pilot scheme to support operator mobility between fusion devices. The Operator Mobility scheme allows operator training on plant systems as well as short 1-2 week visits for operators on any operational topics from technicians to heads of operations. The ECRH network demonstrates well the comprehensive use of the EUROfusion Knowledge Management Framework and thus is described in detail below.

The **ECRH network** has been launched in 2024 in collaboration between EUROfusion and Fusion for Energy involving all European ECRH teams as well as participants from ITER, QST and since 2025 from DIII-

D. The network is a community of practice organised through a dedicated ECRH panel, a representative of each ECRH team, jointly agreeing the topics of the seminars, workshops and training while providing the local organisation of the network activities at their laboratories.

The ECRH network activities include:

- Regular online seminars on operational topics while also providing an overview of the ECRH facilities;
- In-person workshops;
- Joint European ECRH Operator School organized by EPFL with 1-week induction course in Lausanne, Switzerland followed by weekly online classes;
- In-person operator training at ECRH facilities in Europe, ITER and USA using the EUROfusion mobility of operator scheme;
- Publications on commissioning and operational experience in the PPCF Special Issue on Operations; This is a dedicated issue by PPCF focusing on commissioning and operational experience of various fusion devices including the JET tritium operation experience.

There are some basic principles that made the ECRH network as a community of practice work. These include

- **Organised by the community:** 10-20 teams across Europe with guest collaborators from ITER, QST and other laboratories. All members can raise topics that are needed to improve the operational reliability and performance of current devices as much as support commissioning and preparation of operation of future devices. The panel with a representative of each team jointly agree the dates and topics of activities while providing the local organisation of the network's activities at their local laboratory.
- **Inclusive:** all experts from the participating team are welcome at the events. These cover engineers, technicians, scientists from students to retired experts. Events are attended by 60-100 participants.
- **Relevant:** address current problems and questions from both current and future devices.
- **Discussion-focused:** All events include 50+% discussion time. The priority is to facilitate discussion between the teams as well as offer training for the next generation of experts.
- **Flexible:** all events are recorded and available on a dedicated SharePoint and can be accessed at a later time.
- **Training:** the community jointly trains the next generation of operators through dedicated European operator school and local training at the laboratories.
- **Reference material:** collect expert list, create resource and publication database, share documentation on commissioning procedures and operational processes.

The success of the NBI network extended into offers and exchange of spare components, joint work with suppliers and identification of collaboration opportunities between the teams. The next step is to share documentation on commissioning and operational processes with the potential aim to create standards of operation and commissioning for future facilities.

6. CONCLUSION

The rapid growth of fusion research and industry highlights the urgent need to attract, train, and retain a highly skilled workforce. From early STEM engagement to advanced postgraduate training and knowledge management frameworks, the initiatives described demonstrate the breadth of global efforts underway. Ensuring access to education, supporting vocational pathways, and preserving tacit knowledge are all essential to sustaining expertise and engineering capacity. A coordinated, international approach that integrates outreach, higher education, vocational training, and knowledge transfer will be vital to preparing the next generation of fusion scientists, engineers, and operators, and to meet the demands of a growing global fusion industry.

The next decade will be decisive for building the human capacity required to support ITER's operation, the evolving fusion industry, supply chain and in the future, commercial fusion power plants. Workforce expansion must not only focus on increasing the number of trained specialists, but also on broadening the range of disciplines engaged—from plasma physics and nuclear engineering to systems integration, and supply chain

management. Simultaneously, effective vocational training will be critical to prepare technicians and industry professionals who can transition into fusion from other sectors.

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