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Towards strategic agenda for European nuclear education, training, and knowledge management

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ABSTRACT

The key elements of the EU-wide strategic agenda for nuclear education, training, and knowledge management are proposed in this paper. They were developed partly within the ENEN+ and ENEN# projects, to support and consolidate the efforts of the nuclear stakeholders to attract, develop, and retain new talents. The paper considers the projections of needs developed by the European Human Resources Observatory-Nuclear (EHRO-N). It builds on the existing national nuclear education strategies in the EU and beyond and more than two decades of experience with the European Nuclear Education Network (ENEN). The paper outlines and substantiates the most important actions and risks related to human resources, which need to be managed successfully for the EU to contribute to the tripling of the nuclear power generation capacity on the planet by 2050 (as announced in COP28) and to retain its leading role in the nuclear power and non-power applications. The sheer complexity of this challenge calls for high-level strategic support, coordination, and partnership between all nuclear stakeholders, especially those involved in the decision-making. The present situation calls for urgent strategic actions with long-term sustainability.

1. Introduction

A nuclear power plant is with us for a century or more: the lifespan of an already developed and marketed nuclear power plant includes roughly one decade to decide and prepare the documentation, another decade to commission, 6 or more decades of operation, and a few decades of cooldown and decommissioning.

One century brings enormous changes in science, technology, and a social environment. Neat examples include recalling that nuclear fission was discovered less than a century ago in 1938 (Hahn and Strassmann, 1939), followed by the first human-controlled chain reaction in Chicago pile in 1942 (Allardice and Trapnel, 1949). An example of huge social changes that one century might bring is the city of Ljubljana, today the capital of Slovenia, which resided in ten (10) different countries between 1900 and 2000[1].

Sustainable and safe utilization of nuclear power facilities, with individual machines being around for a century or more, therefore clearly requires multiple generations of workforce and strong leadership, or at least fast adaptations, towards the developments in science and society. One would therefore expect that the attraction of new talents followed by the high-class research and higher education of nuclear professionals is a thriving activity enjoying strong support by all stakeholders.

Yet the current state of affairs of nuclear education in many countries, including European Union, is not very encouraging. As (Mahafey,

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[1] Austro-Hungarian empire until 1914, State of Slovenes, Croats and Serbs (1918), Kingdom of Slovenes, Croats and Serbs (1918–29), Kingdom of Yugoslavia (1929–41), Kingdom of Italy (1941–43), Third Reich (1943–45), Democratic Federal Yugoslavia (1945), Federal Peoples Republic of Yugoslavia (1945–63), Socialistic Federal Republic of Yugoslavia (1963–91), Republic of Slovenia (1991-).

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2010) had put it lucidly "*For the past 30 years, ever since nuclear technology was put in hibernation, public education on nuclear technology has nearly ceased. Nuclear engineering programs in technical institutes have dried up, research reactors have been decommissioned and torn down, reactor and auxiliary systems manufacturers have gone out of business or been sold to foreign interests, and nuclear engineers have become authors.*"

Recently, the great utility that the nuclear power technologies may offer in the transition towards non-carbon power sources is being more and more recognized by society at large, which is reflected also at the highest political levels. The most recent example is a pledge by 22 countries to triple the nuclear power generating capacity on the planet by 2050, which was announced during the COP28 in Dubai, UAE, in December 2023. This calls for rather fast growth from about 370GWe of installed nuclear electric power in 2023[2] to about 1.100 GWe in 2050. Adding about 750 GWe of reactors will also require the attraction and development of about 2,5 million new nuclear talents (about 100.000 per year in average), as extrapolated from a recent prediction of about 370.000 new talents for an additional 100 GWe by 2050 in USA (US DOE, 2023). Comparable estimates are also available in France (GIFEN, 2023).

Urgent revival and sustainable strengthening of the (European) nuclear education are therefore considered essential for the future European leadership in the utilization and development of nuclear power and non-power technologies. The sheer complexity of this challenge calls for a high level of support, strategic coordination and partnership between all nuclear stakeholders, especially those involved in all levels of decision-making.

This paper proposes some key elements of the EU wide strategic agenda for nuclear education, training and knowledge management, which might be useful in the strategic coordination of the nuclear education, training and knowledge management in EU. It builds in the significant part on the developments within the ENEN+ (ENEN+, 2017) and ENEN# (ENEN2Plus, 2022) projects and touches mostly the non-technical constituents and related risks. The paper is organized as follows:

- Section 2 Setting the stage briefly outlines the decline of nuclear education since the 1980-ies and summarizes the current situation. It also summarizes the status of the national nuclear workforce development strategies in the EU and beyond.
- Section 3 The main challenges outlines the main non-technical challenges, resulting mostly from the half a century of decline, the long-term nature of nuclear facilities and technologies, and increasing complexity of the nuclear regulatory regimes worldwide.
- Sections 4 Discussion and 5 Strategic Vision outline the goals, the main challenges with related risk for the future. They also identify the key nuclear stakeholders that should manage those challenges and risks.

In this paper, the discussion is focused on strategic, therefore less technical topics. Discussions on curricula are beyond our scope and may be found elsewhere, for nuclear engineering in (Moons et al., 2005).

More details and supporting materials for the discussion and proposals in this paper can be found in (Cizelj et al., 2021a) and (Cizelj et al., 2021b).

2. Setting the stage

The clear signs that nuclear higher education might be dwindling were noted and reported at the end of the 20th century in high-level documents (CCE Fission, 2001; Corradini et al., 2000; INSAG, 2001; OECD/NEA, 2000). These documents included comprehensive sets of bottom-up and top-down recommendations to preserve and improve nuclear higher education and training. A vivid illustration of the circumstances leading to this was proposed by a "four season model" (Chung, 2006), which connects the attraction and development of the nuclear workforce to the stages of the maturity of the nuclear industry and research. Spring (e.g., 1940–1950) was enabled through strong research activities. Summer (1960–1980) followed by fast industrialization, reaching Autumn (1980-ies) and saturation both in construction of new plants and in recruitment. The first signs of the decline in nuclear research and education activities noted in autumn then started to be fully developed in the Winter (1990–2000).

Many initiatives followed, including the establishment of the European Nuclear Education Network (ENEN) Association in 2003 (Moons et al., 2005). Those initiatives enabled for the most part bottom-up activities, including pooling the teachers, infrastructures and students. These initiatives did receive important top-down support. ENEN, for example, has been supported for more than 20 years through projects by the European Commission within the EURATOM Fission Training Schemes (see also section 2.4). A historic view with more details on these initiatives and their main outcomes is available in (Giot et al., 2024).

Some more information about the strategic activities of USA, some EU member states, China, IAEA and OECD/NEA is outlined below.

2.1. Revival of nuclear education in the USA

A national statistic of nuclear engineering graduates in the USA (ORISE, 2017) has been established in the 1960's. The history is depicted in Fig. 1, clearly showing the dwindling number of graduates at the end of 1990's and the strong growth thereafter, which was to a large extent following the implementation of recommendations developed in (Corradini et al., 2000).

Recently, various nuclear strategic visions were adopted in the USA. Examples include documents by the US Department of Energy (US DOE, 2021), Nuclear Industrial Association (US NIA, 2021) and American Nuclear Society (ANS, 2021). The stakeholders "responsible" for the strategic actions facilitating workforce development through science are US Department of Energy (DOE) and industry. A high degree of cooperation and coordination of DOE and industry with academia is therefore envisioned and expected.

Recently, an in-depth analysis of the talents needed in USA to achieve 200 GWe nuclear generating capacity by 2050, with a ceiling set at 13 GWe/year, has been published (US DOE, 2023). It calls for the recruitment and development of 376.000 new nuclear talents.

2.2. International Atomic Energy Agency (IAEA)

Organizations working together, as for example within ENEN, can provide more efficient and cost-effective educational programs that can be established far quicker than just one organization working independently. There may also be political drivers to ensure that funding is spread between organizations to create more opportunities either geographically to perhaps reduce the cost to students, or technologically, ensuring that all required courses and topical areas are developed equally.

This coordinated approach to the networking of nuclear education and training in Europe has been in part echoed by the IAEA also in other regions by establishing the networks: Asia, Latin America, Africa and the Eurasian Economic Community States, with the support of the International Atomic Energy Agency, have all established networks:

- ANENT – Asian Network for Education in Nuclear Technology, serving Asia with only minor involvement of China and Japan (Guo, 2022);
- LANENT – Latin American Network for Education in Nuclear Technology (Barrachina and Picado, 2022);

[2] IAEA Power Reactor Information system https://pirs.iaea.org.

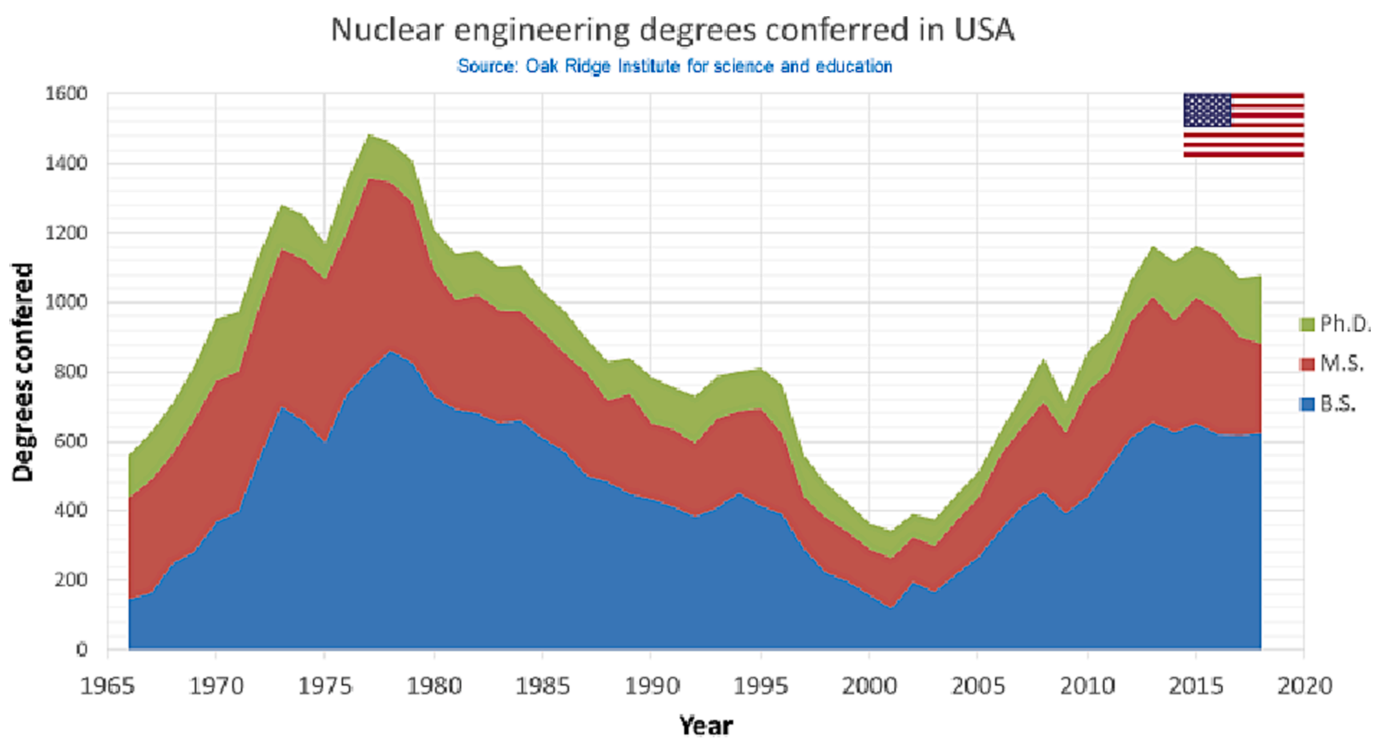

Fig. 1. Nuclear engineering degrees conferred in USA (ORISE, 2017).

- AFRA-NEST - AFRA-Network for Education of Nuclear Science and Technology (Hassan, 2024);
- STAR-NET - Regional Network for Education and Training in Nuclear Technology serving the Eurasian Economic Community States (Kosilov, 2022).

IAEA pursues many other activities related to the education, training[3] and knowledge management[4].

At the time of writing this paper, a very important activity of the IAEA entitled “Status and Trends in Nuclear Education in Member Countries” is on-going. The final report might have a strong informative value for global strategic planning of nuclear Education, training and knowledge management (ETKM) and might influence the activities in EU, especially as the current and possible also future situation in nuclear ETKM in China, Russian Federation and USA may be much more vibrant than in EU.

2.3. Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA)

The NEA launched in 2019 the Nuclear Education, Skills and Technology (NEST[5]) Framework in partnership with its member countries to help address important gaps in nuclear skills capacity building, knowledge transfer and technical innovation in an international context. The NEST Framework is developed as an NEA joint undertaking gathering private and public organizations from interested countries (not necessarily NEA member countries). The goal of NEST is to:

- energize advanced students to pursue careers in the nuclear field by proposing a multinational framework among interested countries to maintain and build skills capabilities;
- establish international links between universities, academia, research institutes and industry;
- attract scientists and technologists from other disciplines to examine nuclear technology issues and involve such actors in the resolution of real-world problems.

NEST appears to be the only current activity of NEA with the direct focus on ETKM.

2.4. Nuclear training and education framework in European Union (EU)

From the outset, the Euratom Treaty[6], establishing the European Atomic Energy Community (EAEC or Euratom) in 1957, identified education and training as key to the sustainability of the nuclear industry. Promoting research and ensuring the dissemination of technical information were set as one of the eight key activities around which the Treaty was structured. Since then, the Euratom Research and Training programs have put a strong emphasis on developing nuclear skills and competence, this to allow Europe to maintain world leadership in nuclear safety and waste management and to attain the highest level of protection from radiation.

Education and training have then always been a key concern within European nuclear energy programs and the respective requirements and obligations have been laid down in key documents such as the Euratom Treaty, the IAEA Convention on Nuclear Safety and outlined in different EU directives and regulations. This legal framework not only calls for each EU Member State to take the necessary measures with regard to teaching, education and vocational training but also establishes nuclear E&T as a crosscutting horizontal activity in the Euratom Work Program to be supported by coordination actions & innovative synergies.

Nuclear research, education, training and knowledge management, for which the primary responsibility resides with the EU member states, is complemented and facilitated by the European commission. Examples

[3] https://www.iaea.org/services/education-and-training.

[4] https://www.iaea.org/topics/nuclear-knowledge-management.

[5] https://www.oecd-nea.org/jcms/pl_21786/nuclear-education-skills-and-technology-nest-framework.

[6] Consolidated version of the Treaty establishing the European Atomic Energy Community, 2012/C 327/01.

include the current Euratom Research and Training Program (2021–2025)[7], a complementary funding program to Horizon Europe, which covers nuclear research and innovation. It sets maintaining and further developing expertise and competence in the nuclear field within the community, and making improvements in the areas of education, training and access to research infrastructures, as key priority objectives. Another example is activities of the Joint Research Center of EU. These include a wide variety of education and training activities (Cihlar, 2022) and access to research infrastructures (Seibert et al., 2024).

2.5. National nuclear strategies in selected EU member states

A number of countries in EU and beyond did publish strategic documents supporting the research, innovation and operation of nuclear facilities. Brief summaries of the relevant documents from the EU members states are outlined below. The national strategies from countries beyond EU mentioned in this paper include USA (section 2.1) and China (section 2.6).

An inquiry among the ENEN members in 2019 revealed five documents, which were deemed by the ENEN members relevant for the national nuclear education and training strategies (Cizelj et al., 2021a).

The oldest nuclear national strategy mentioning also the nuclear education appears to have been published in Romania in 2002 (Romania, 2002). The next one in the chronological order appears to be the Hungarian "National Energy Strategy 2030" published in 2012 (Hungary, 2012). This document clearly recognizes strategic need for nuclear power and related education and training programs and places, together with the vision for the future, into the national energy strategy framework: *"…with regard to the shortage of energy experts and with a view to achieving the objectives of the Energy Strategy, high quality vocational education in energy needs to be revived as soon as possible, with particular regard to the launching of the multi-level training of experts skilled in the mapping of energy saving options and the utilization of renewable energy sources. The human resource requirements of the creation of the new nuclear blocks also require the implementation of a substantial educational and training program."*

The Finnish Nuclear Energy Research Strategy followed in 2014 (Finland, 2014), clearly supporting the development of the Finnish national nuclear workforce through coordinated research activities: "*Internationally high-quality Finnish expertise and research will secure the safe, sustainable, and competitive use of nuclear energy and promote nosiness opportunities." A special fund has been put together to directly support nuclear research from the sales of nuclear electricity*[8].

Poland also started the revival of the country's nuclear power program with a strategic document published in 2020 (Poland, 2020). The government clearly recognizes its responsibility of the timely workforce (and infrastructure) development for successful and safe operation of the future nuclear power plants: "*Providing highly educated and well-trained staff capable of actively co-creating a unique safety culture is one of the most important tasks in preparing for the construction and operation of a nuclear power plant. In view of the need to ensure the high competence and efficiency of nuclear power sector workers, proper planning, training and management of staff is essential. … Recent experience with the deployment of nuclear power in the United Arab Emirates indicates that insufficient staffing may lead to a delay in the launch of the NPP. It should also be noted that liability for untimely HR preparation for UAE NPPs is borne by the government and the plant operator / investor, not the technology vendor.*"

The proclaimed closures of operating plants in many countries may have contributed to further dwindling of nuclear education. On the other hand, it appears that the countries that decided to cease operation of nuclear power plants also felt a much stronger need to give power to the top-down approaches to the nuclear education and training: it appears that Germany is the only member state in the EU with a dedicated nuclear education strategy published in 2020 (Germany, 2020), therefore nearly a decade after the proclaimed stepping out of nuclear power in 2012.

A common trait of all above mentioned documents is that they rely on nuclear research as the main driver for workforce development. One may therefore conclude that there is large degree of agreement at the strategic level that "know-why" and nuclear education are essential prerequisites for the successful "know-how" and nuclearization. For further details on "know-why" and "know-how" see section 3.2 and (Cizelj et al., 2023).

2.6. Chinese nuclear safety strategy

A document entitled "Nuclear Safety in China" (China, 2019) has been released in 2019. Nuclear higher education is mentioned in the section "Ensuring Effective Regulation of Nuclear Safety". This implies that the nuclear higher education is seen as one of the major pillars of the nuclear safety in China and places the strategic developments of the higher education system at least partially in the hands of the nuclear regulator: "*To meet the requirements of the development of the nuclear sector and nuclear safety regulation, China has given top priority to strengthening the professional teams … the state has set up a national nuclear safety expert commission composed of 25 academicians of the Chinese Academy of Sciences and the Chinese Academy of Engineering …China has established an education and training mechanism involving institutions of higher learning, research institutes, and enterprises.*"

The document (China, 2019) asserts that more than 3.000 nuclear students enrolled at 72 universities in 2019.

3. The main challenges

Today, more than 20 years after the first signs of dwindling nuclear education, the main concerns persist. A vivid explanation was proposed by (Chung, 2018) pointing out very plausible reasons for the persistence, including (1) tendency to solve the easy problems first, and (2) tendency to be more concerned with "how" and "what" rather than "why".

These reasons are consistent with the experience and observations of ENEN, which are briefly outlined below. Other relevant documents discussing the challenges, opportunities and risks related to the rather weak progress in nuclear ETKM after 2000 include (European Commission, 2011; Grimes and Nuttall, 2010; OECD/NEA, 2004, 2012; Simonovska and Estorff, 2012).

It is noted that nuclear energy currently has varying degrees of support in the countries of the European Union. Nevertheless, education and training are required across all three phases - construction, operation and decommissioning - of a nuclear plant. It is therefore imperative that sustainable education and training programs exist to support the full life cycle of nuclear power plants.

The main challenges, as identified in (Cizelj et al., 2021a), are outlined below. Some possible solutions are then proposed and discussed in sections 4 and 5.

3.1. How many talents do we need?

A possible reason for persistent challenges may be rather intricate counting of nuclear graduates. In the USA, for example, a national statistics for nuclear engineering graduates (ORISE, 2017) has been established in the 1960's. The history of graduates is depicted in Fig. 1.

Dedicated collection of such numbers is necessary, since the nuclear engineering graduates clearly fall deeply below the resolution of the

[7] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/euratom-research-and-training-programme_en.

[8] https://safer2028.fi/.

statistical data on tertiary education collected for example by UNESCO[9] or EUROSTAT[10].

The efforts of European Human Resources Observatory-Nuclear (EHRO-N) to collect the numbers of supply and demand of nuclear graduates in EU have resulted in less frequent and possibly also less accurate statistics (Eriksen et al., 2019; Simonovska and Estorff, 2012) than available in the USA, which may need to be further refined and improved in the future. The diversity of the education systems being organized by the EU member states and the proprietary data on the workforce needs by the industry might be among the main reasons for such a state of affairs. Nevertheless, the 2833 graduates in nuclear engineering or energy reported in 2010 is much more than the 2167 reported in 2017 (Eriksen et al., 2019) and might confirm the existence of persistent challenges causing the dwindling of the EU nuclear education.

The distribution of the 2017 EU nuclear engineering and energy graduates by gender and the level of degree is depicted in Fig. 2.

3.2. Know-why versus know-how

High tech industry, including nuclear, depends on people with very diverse degrees and specialties of education and training. The quest for efficiency, reliability and safety, stimulated in part by declining nuclear education, the pressures by competition and evolving regulations, to mention a few, might guide the industry towards more internal training, directed naturally much more towards "know-how" than 'know-why'. Important driver towards such developments may also be the fact that the highly safe industries strongly rely on "know-how" documented in considerable details in operating procedures and regulations. An illustration of main differences between the "know-why" and "know-how" is depicted in Fig. 3.

The dwindling higher nuclear education, aiming more at "know-why", might be therefore compensated, at least for a short while, with more intensive training (e.g., "nuclearization" of non-nuclear graduates) by the industry, aiming more at "know-how". In this way, the main pipeline for attraction and development of the new nuclear talents becomes the "nuclearized" pipeline at the expense of the "nuclear" pipeline (Fig. 4). This is another possible perception of the challenges in nuclear education that persists since the 1990's.

In the short term, the prevalence of the "know-how" or "nuclearization" approach may appear to increase the efficiency and the safety record of the industry. In the medium and longer term, however, the prevalence of the "know-how" acquired in proprietary trainings may contribute to some important risks, which might develop gradually and intensify with time as a surprise to the community. These potential risks include (Cizelj et al., 2023):

- *"Reduced ability to manage the unexpected situations, namely the "unknown-unknowns" For further discussion see for example (*Higley, 2017*), (*Cheung, 2021*) and (*Saito, 2016*)."*
- *"Reduced potential and/or need for innovation. This is usually followed by the loss of competitiveness, especially against other competing technologies, and the loss of interest of young creative talents. This suggestion is to some extent supported by the fact that the R&D investments of nuclear industry are not reported among the energy industry investments in R&D (*Grassano et al., 2022*). Also, it might offer a plausible explanation for the persistent diffusion of nuclear experts from EU-based nuclear utilities to other service providers in the period 2010–2018 (*Eriksen et al., 2019*)". See also* Table 1.
- *"Perception of high expertise and low credibility of the nuclear industry in the public (*Turcanu et al., 2018*). Preferential internal and proprietary training could namely, as collateral damage, further disable the interest for and performance of the publicly available nuclear higher education. After a decade of two of such developments, one might notice an absence of nuclear expertise outside of the industry and the regulator, which may seriously degrade the public perceptions on the safety, reliability and credibility of all nuclear facilities. Further, as noted by (*Saito, 2016*) and (*Uršič et al., 2021*), this may also degrade the competence in organizational levels of defense in depth outside the nuclear industry, namely in the regulatory bodies, technical support organizations and last, but not least, in the last level of defense: public at large, including academia."*

The consideration of the above risks clearly indicates advantages of "Nuclear" over "Nuclearized" talent supply and development pipelines (Fig. 4), which include:

- Serves more stakeholder communities (industry, regulators, technical safety organizations, academia and public at large).
- Contributes more to the transparency of nuclear technologies within general public, as it operates predominantly in the public domain and not within the proprietary constraints of industrial "Nuclearization".
- Strengthens the defense in depth in terms of knowledge. Two immediate arguments for this are (1) it provides the non-proprietary knowledge to many more stakeholders and (2) looks far beyond the procedural knowledge (know-how).
- Facilitates more research and innovations, since academia very rarely operates within only proven technologies.
- Younger talents may be much more open towards creative opportunities that might improve the world, for example new reactor designs including Small and Modular Reactors (SMR), as compared to serving in an ultra-reliable and therefore also rather boring industry. The notion of boring industry could also at least in part explain the drifting of nuclear experts in EU away from the nuclear utilities and vendors to other sectors (Table 1).

Last but not least, complementary operation of both supply pipelines contributes to diversified safety cultures. The reason for this lies in fundamentally different approaches towards managing the errors. The industrial environment benefits from prevention of errors and, when successful, minimizes learning from errors. Academia on the other hand thrives on learning from errors. Experience in both environments could therefore provide the person with much wider error detection and management attitudes that any single of both environments could offer.

3.3. Nuclear knowledge communities

Many nuclear 'knowledge communities' have developed over the decades of utilization of nuclear power and non-power technologies. These can be seen as ever stronger specialization of experts, probably being a natural consequence of increasing complexities in technologies and regulations and the clear tendency towards the "know-how" and "nuclearization". This process of ever stronger specialization of experts might be continuing and even accelerating with the ever-stronger development and deployment of new nuclear technologies, as for example Small and Modular Reactors and Advanced or Gen IV reactors.

Many of the nuclear 'knowledge communities' have already approached ENEN for cooperation and coordination, including nuclear engineering, radiation protection, management of radioactive waste, fusion engineering, medical applications, nuclear security, nuclear safeguards, nuclear materials, nuclear safety assessment (TSO), nuclear culture for safety, radio chemistry and decommissioning of nuclear installations, to mention a few. More information on the historic developments in connecting those communities with the activities of ENEN is available in (Giot et al., 2024).

There are some nuclear 'knowledge communities' that have not yet sought cooperation or coordination. The most important among those

[9] https://data.uis.unesco.org/ Natural Sciences, Mathematics, Engineering….

[10] https://ec.europa.eu/eurostat/databrowser/view/sdg_04_20/default/table?lang=en, Science, mathematics and computing, engineering, manufacturing and construction.

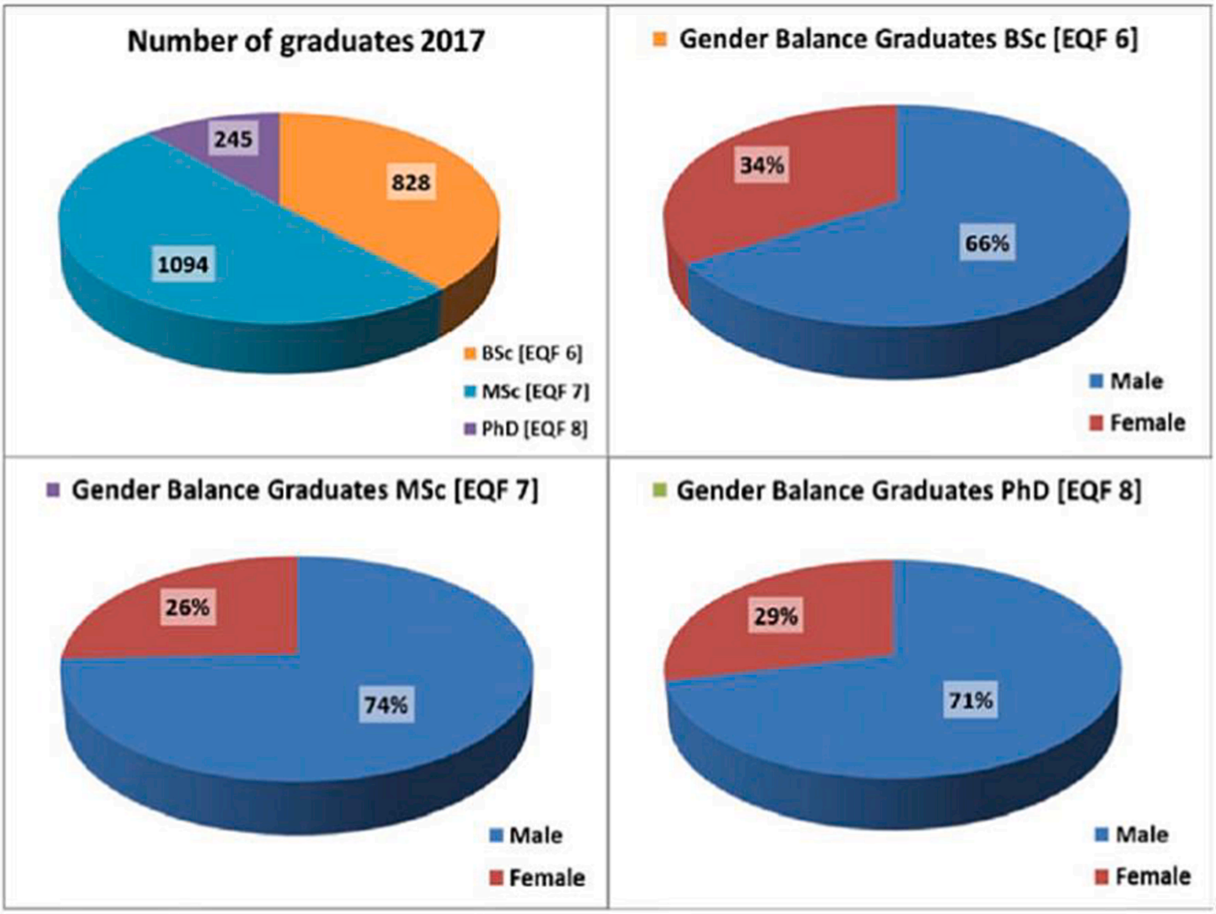

Fig. 2. Number of graduates and gender balance between students and education levels in nuclear engineering and nuclear energy studies in 2017 (Eriksen et al., 2019).

might be the nuclear regulatory community. Let us reiterate the observation in section 2.6 that, in China, the nuclear higher education is seen as one of the major pillars of the nuclear safety. As a consequence, the nuclear regulator is tasked at least in part with the responsibility for the strategic developments of the higher education system.

The possibly unwanted and perhaps also unexpected consequence of the strong and increasingly independent nuclear 'knowledge communities' could be escalating competition for talents between nuclear communities. Such developments may hinder the cooperation between nuclear knowledge communities, which is strongly needed in competition for talents with other – non-nuclear – complex or high technologies, especially with the not very optimistic demographic developments and low interest of young people for careers in Science, Technology, Engineering and Mathematics (STEM).

Another unwanted consequence might be a perception of considerable complexity of nuclear education. Such perception might develop among the prospective students, who would need to choose their individual specialization before developing a solid overview of available nuclear specializations or 'knowledge communities'. One of the obvious and immediate consequences could be a perception of reduced attractivity of nuclear education and training.

3.4. Steady supply vs highly cyclic demand

Experience shows that construction of nuclear power plants comes in waves. In Europe, for example, the vast majority of the facilities were built in the 1970s and 1980s. Consequently, the recruiting and development of personnel for operation and other stakeholders has also been done in waves (e.g. 1970 and 1980s for the first wave, 2010–2020s for the replacement of the first generation). This will be, recalling that nuclear power plant is with us for a century or more, repeated also in the future. Between those waves, the demand for new personnel is generally very limited.

In general, the higher educational systems need sustainable and stable conditions and might need very specific support through the times with low demand to avoid university departments being shut down on the grounds of too low demand and/or when professors retire. Such support may be necessary, among others, because of rather long times involved in the development of new faculty (e.g. up to 20 years).

4. Discussion

A common trait of the current challenges in nuclear education, training and knowledge management, mentioned above, appears to have been developed in the absence of strong strategic guidance or, in other words, too strong reliance on the bottom-up approaches practiced independently by the diverse nuclear stakeholders involved. These might have over the decades resulted in the domination of know-how or nuclearized expertise over know-why or nuclear expertise and creation of very many specialized nuclear knowledge communities competing for the talents with each other instead of with other – non-nuclear - high-tech industries. These, together with increasing complexity of nuclear technologies and regulations combined with less and less nuclear research and education outside of the nuclear industry, contributed to diminishing public acceptance of nuclear technologies.

The bottom-up approaches implemented in the EU to revive the nuclear education and training practiced during the last two decades were on the whole satisfactory to maintain the education systems and

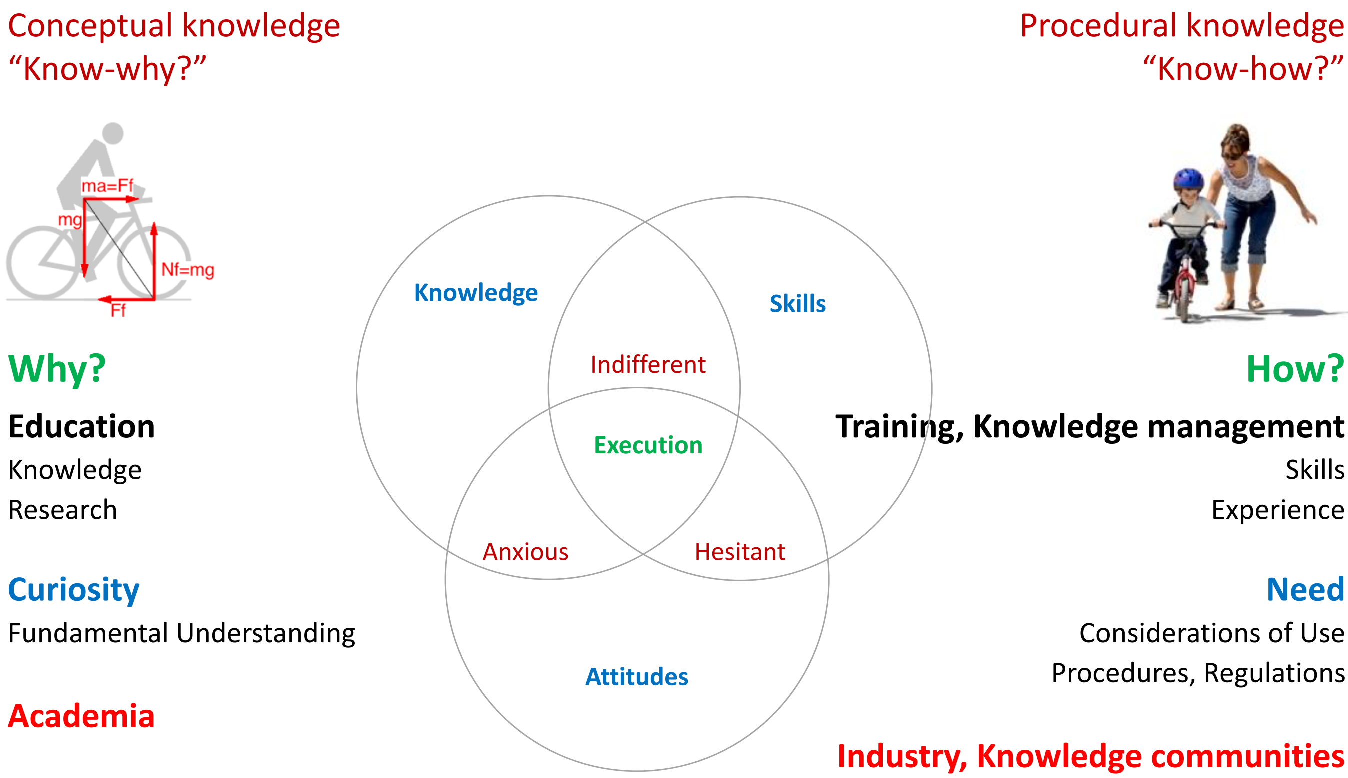

Fig. 3. Main features of the "know-why" and "know-how" (Cizelj et al., 2023).

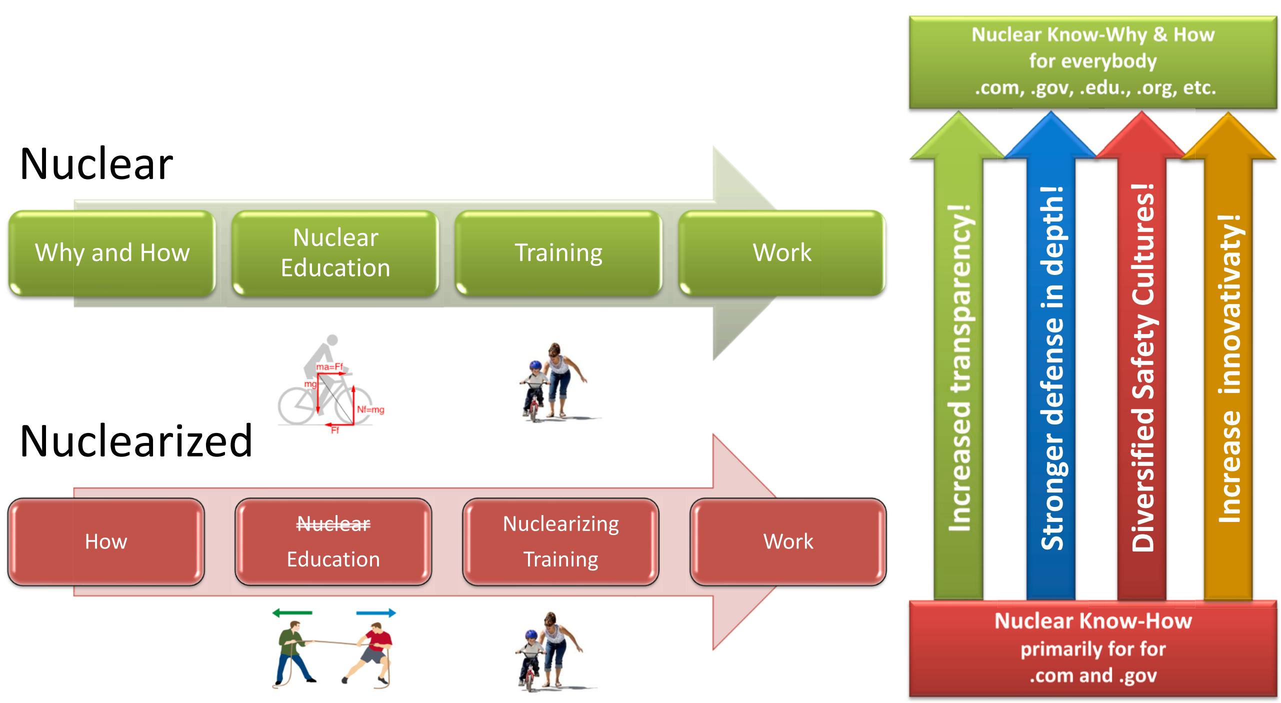

Fig. 4. The main nuclear talent attraction and development pipelines. ().
Adapted from Cizelj et al., 2021b

generate warnings to the decision makers. They were unfortunately not satisfactory to attract sufficient numbers of new talents and did not lead to substantial innovations to nuclear (power) technologies. The proclaimed closures of operating plants in many countries may have contributed to further dwindling of the nuclear ETKM.

On the other hand, it appears, perhaps paradoxically, that the countries that decided to cease operation of nuclear power plants also felt a much stronger need to give power to the top-down approaches to the nuclear education and training: it appears that Germany is the only member state in the EU with a dedicated nuclear education strategy published in 2020 (see section 2.5).

A number of countries in EU and beyond did publish strategic

Table 1
Distribution of nuclear experts in nuclear sectors in 2010, 2014 and 2018 (Eriksen et al., 2019).

Sector	2010 [%]	2014 [%]	2018 [%]
Utilities	51	25	7
Vendors & Big Suppliers	18	4	4
Research and Design	13	15	13
Design, Engineering, Manufacturing, and Maintenance	7	36	36
Waste Management and Decommissioning		14	7
Regulatory Authority and Technical Safety Organizations (TSO)		4	16
Fuel Fabrication, Enrichment, and Supply		1	16
Consultancy		1	2
Academic			1
Training Provider			
Other	11		

documents supporting the research, innovation and operation of nuclear facilities. A common trait is that they rely on the nuclear research as the main driver for the workforce development, as do the nuclear strategies prepared by different stakeholders in the USA, China and EU. One may therefore conclude that there is large degree of agreement at the strategic level that “know-why” and nuclear education should have a preference over the “know-how” and nuclearization.

An interesting observation is that nuclear higher education in China with fast developing nuclear power program, with more than 3.000 nuclear students enrolling annually in more than 70 universities, is discussed in the section on nuclear safety, suggesting that the responsibility is with the nuclear regulator (section 2.6).

It appears that stronger top-down (strategic) approaches may be needed to maintain and further develop the nuclear education and training in the future, as practiced in the USA and China. A well-balanced combination of strengthened top-down and bottom-up approaches receiving support from all nuclear stakeholders may provide the optimal basis for future actions and may facilitate much easier balancing of the main challenges, as summarized in Table 2.

This vicious circle, that started with the preference for know-how over know-why and with the lack of top-down strategic guidance, will have to be broken urgently. This may enable the sustainable growth in the higher education and research in the future without accelerating the competitiveness between the nuclear knowledge communities and the gaps between the cyclic demand and steady supply of developed new talents.

The present situation in nuclear ETKM in EU with more than two decades of persisting challenges is calling for urgent strategic actions aiming for long term sustainability. A strategic top-down action by the governments and European Commission is needed to help all nuclear stakeholders to improve the cooperation and coordination of existing and future innovative education approaches.

Table 2
Summary of main challenges with plausible solution(s) and responsibilities.

Challenge	Solution	Responsibility
Top-down vs. bottom-up	Appropriate balance	**Top-down:** strategic guidance/support by governments through nuclear research and higher education strategies. **Immediate start and long-term support needed**. **Bottom-up:** self-sustaining in case of good market conditions and/or good strategic support
Know-why vs. know-how		Self-sustaining in case of good market conditions and/or good strategic support
Competition vs. cooperation		
Complexity vs. simplicity		
Steady Supply vs. Highly Cyclic Demand		

The most important or critical activities for the sustainability and further development of nuclear E&T in EU should be directed towards the attraction and development of new talents, supported by coordinated actions of all stakeholders. Development of new courses, methods and initiatives are of limited value without sufficient number of students.

5. Strategic vision

In the first step, with some urgency, we will need to break the vicious circle of “know-how” dominance over “know-why” and to overcome the tendency to solve the easy problems first. This vicious circle has been developing for decades and resulted in a continuous decline in the interest of youngsters for careers in nuclear and might today well be an integral part of the nuclear corporate culture. The more difficult approach, namely establishment of balance between “know-why” and “know-how”, will have to fit not only the boundary conditions dictated by the markets, but will also require long-term strategic planning, communication, cooperation, investments, etc., of all nuclear stakeholders.

Indeed, the future nuclear professionals will have to be enabled with a rather wide knowledge, skills and attitudes. The shared goals of the nuclear professional community may be expressed as:

- Attract the best new nuclear talents.
- Develop technical specialists, enabled to work with increasingly complex technologies and regulations in increasingly multidisciplinary and multicultural (international) environments. Hand on experiences with different nuclear technologies, communities and cultures as early in the education process as possible appear essential.
- Retain attracted and developed talents in nuclear professions.

These goals are further discussed below.

Please note that a coordination between different nuclear ‘knowledge communities’ and also different nuclear stakeholders (e.g., government, regulators, industry, academia, technical safety organization and last, but not least, general public), as in parts already practiced today by ENEN, is considered to be very useful also for successful future developments of nuclear ETKM.

The concept of “Attracting, developing and retaining” new nuclear talents has namely been proposed by ENEN in the Horizon 2020 project (ENEN+, 2017). Further developments are expected in the ongoing Horizon Europe project (ENEN2Plus, 2022). ENEN, ENEN+ and ENEN2Plus are bottom up initiatives with short term support as project cofounded by the European Commission. Their long-term sustainability would benefit immensely from a top-down strategic and support, within the EU possibly in a format of a program or direct action of the European Commission.

5.1. Attract the best new nuclear talents

Attracting new talents of appropriate quality and quantity is the prerequisite of any successful ETKM activities. Visible and interesting job opportunities are among the most successful attractors of new talents. These might give a person better perceptions of career stability and appreciation of the time and efforts invested into the excellent education and training.

Job opportunities in academia are usually percieved as interesting research projects and attractive research infrastructure. These in turn require strong and stable support through research grants by governments and industry. Interesting research opportunities, for example in researching and developing different SMRs might be among the decisive opportunities in successfully competing for the best talents with other high-tech fields.

Job opportunities in industry on the other hand require a good standing of industries in the markets today and solid strategic orientations towards the business opportunities in the future. In general, if a topic is developing fast in academia, it might start developing good business opportunities in five to ten years in the future. On the other hand, if a topic, as for example nuclear engineering, is dwindling in academia, fading away of the nuclear engineering solutions in the business environment five to ten years later should not come as a surprise. And, possibly, here we should mention again that the nuclear power plant is with us for a century. This also requires a long-term or strategic approach to the attraction and developing the talents.

Successful attraction (including development and retention) of the new talents should fully appreciate the diversity of the contemporary generations. In this we shall note that the GenX (1966–1976), sometimes also considered as the best educated generation, is today in the most of the decision-making positions. Other relevant generations together with their very basic, perhaps somewhat archetypal descriptions, include:

- The Xennials (1976–1985): more inclined to the GenX than to Millennials and just starting to feel more attracted to technology which did not yet influence too much their appetite for experiencing new things in rather short time.
- Millennials (1980–1994): the generation that appears to be heavily influenced by the internet, speed, diversity, flex-time, work from home, freelancing, etc. The millennials may value motivation over monetary goals and appear to be more task than time-oriented (quality over speed).
- Gen Z (1995–2012): this generation appears to be more tolerant, less risk taking, more likely to consider themselves first. They also value a lesser amount of “in person” and “face to face” contact with others than Millennials or Xenials.

Attracting of new talents therefore requires coordinated approach of industry, academia and governments, in particular in the following actions:

- Pro-active role of future employers including coordination with nuclear universities.
- Appealing activities for high school pupils and teachers.
- Appealing activities for B. Sc. students.

Strategic optimization through on-going estimations of future needs, performed for example by the EHRO-N and supported by the governments and/or industry, would be advantageous. Another great facilitator for the attraction of new talents may also be a broken vicious circle of “know-how” dominance over “know-why”.

5.2. Develop new talents

After attraction, the new talents need the best development available. Ideally, the “nuclear” workforce development pipeline should have priority before the “nuclearized” workforce development pipeline (Fig. 4). In particular, the following actions appear to be of strong importance here:

- Excellent higher education including ample and interesting research opportunities.
- Extracurricular activities for students, e.g. internships in industry and regulatory bodies (mixing cultures, developing social & communication skills), access to research infrastructure, mobility support and career guidance (mentorship from academia and industry, coaching by older students, alumni, etc.).
- Professional training (both with proprietary and publicly available knowledge).

Strategic optimization through on-going estimations of future needs and workforce pipeline capacities, performed for example by the EHRO-N and supported by the governments and/or industry, would be advantageous.

5.3. Retain attracted and developed talents

Retaining the attracted and developed talents is, in analogy with the knowledge management, primarily the task of end-users, including industry and regulators. Academia could support them in part in the following important activities:

- For existing staff, intensify lifelong learning and support for career development, provide creative and interesting working environment.
- Better prepare for the needs and perceptions of the new generations (e.g., X, Y, Z and Millennials).

Here, as in other activities that would fall into the ‘knowledge management’, the strategic planning, and communication with academia, is predominantly in the interest of the industry and regulators.

6. Conclusions

Nuclear knowledge has been one of the major achievements of mankind. It has made many significant contributions to science and technologies beyond nuclear power. Examples include diagnostics through imaging and a variety of therapies in medicine, sterilization in food processing, and diagnostics in industry, forensics, archaeology and geology, among others.

We believe that the time has come for all nuclear stakeholders to establish and follow a common strategic goal: preserve, maintain and further develop this valuable knowledge for present and future generations. The present situation in nuclear ETKM in EU with more than two decades of persisting challenges is calling for urgent strategic top-down actions by the governments and European Commission to help all nuclear stakeholders improve the cooperation and coordination of existing and future innovative education approaches.

The sheer complexity of this challenge calls for high level of support, coordination and partnership between all nuclear stakeholders, especially those involved in all levels of decision-making.

The following essential goals of the future nuclear education, training and knowledge management have been identified and elaborated:

- Attracting new talents of appropriate quality and quantity is the prerequisite of any ETKM activities. Visible job opportunities and attractive research activities are among the most successful attractors of new talents.
- After attraction, the new talents need the best development available. Ideally, the “nuclear” or “know-why” workforce development pipeline should have priority before the “nuclearized” or “know-how” workforce development pipeline.
- Retaining the attracted and developed talents is, in analogy with the knowledge management, primarily the task of end-users, including industry and regulators.

Strategic optimization of the above strategic goals through on-going estimations of future needs and workforce pipeline capacities, supported by the governments and/or industry, would be indispensable.

Coordination and possibly further integration of strategic research and ETKM agendas of different nuclear communities and different nuclear stakeholders, as already practiced in part by ENEN, is also considered as a very important activity in the future.

CRediT authorship contribution statement

Leon Cizelj: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Csilla Pesznyák:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Jörg Starflinger:** Writing – review & editing, Investigation, Data curation. **Gabriel Lazaro Pavel:** . **Franck Wastin:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Eirini Michailidou:** Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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