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Sustaining regional Nuclear Human Capacity Building in Europe

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ABSTRACT

Nuclear science, a pillar of human advancement in the last century, contributes significantly to clean energy and advanced medical care worldwide. This work highlights the critical importance of preserving nuclear human capacity in Europe to maintain a robust pool of expertise and nuclear Education and Training (E&T) infrastructure. Since 2000, the Organization for Economic Co-operation and Development - Nuclear Energy Agency (OECD-NEA) has expressed deep concern regarding the potential shortage of human resources in the field of nuclear science. The European Human Resources Observatory for Nuclear (EHRO-N) provided insight into the actual human resource levels needed in the nuclear industry in Europe, and this concern remains prevalent in the international community as of the year 2023, especially considering the projected nuclear power capacity by 2050.

Given the distinctive and diverse challenges encountered within Europe, a novel quadrangular analysis model is introduced to facilitate the understanding of the diverse Nuclear Human Capacity Building (NHCB) development scenarios in the region.

In the European Union (EU), concerted efforts were initiated in 2003 to establish regional networking activities dedicated to nuclear E&T. Since then, a wide range of nuclear stakeholders, including universities, research centers, industry representatives, technical support organizations, and regulatory bodies, have come together in a bottom-up approach to tackle the different NHCB scenarios in Europe, challenged by a variety of public acceptance, a weakly coordinated nuclear policy top-down approach and the cyclical demand of human capital caused by nuclear construction projects. Their collective goal has been to shape a European nuclear E&T ecosystem capable of addressing potential gaps in human resources within the European region.

Drawing from the accumulated experience of coordinated European nuclear E&T and knowledge management projects, primarily funded by Euratom, a human-centered and generic NHCB Regional Collaboration Framework Model is proposed to support future coordination efforts in this scientific ecosystem. It is designed to serve as a communication tool for both top-down and bottom-up initiatives from governments, public and private institutions in the EU.

The insights and know-how developed by the nuclear E&T community extend beyond their specific domain, offering valuable lessons to the broader nuclear scientific community as well as other industries facing similar challenges in attracting, retaining, and developing human talent.

1. Nuclear E&T background in Europe

The Nuclear E&T collaboration in the European region has its origin set on 25 March 1957, when the Treaty establishing the European Atomic Energy Community, Euratom, was signed also to create a specialist market for nuclear power in Europe, so as to develop the nuclear energy and distribute it to its member states while selling the surplus to other non-member states (European Parliament, 2022).

In 2021, the European Commission's (EC) Joint Research Centre, conducted a review to assess nuclear energy generation under the "do no significant harm" criteria, concluding that its analyses did not reveal any science-based evidence that nuclear energy does more harm to human

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health or to the environment than other electricity production technologies already included in the Taxonomy as activities supporting climate change mitigation (EC Joint Research Centre, 2021). Being a low carbon energy, nuclear energy is considered an asset in fighting climate change, meeting the increasing energy demands and the need for energy security (Mathew, 2022).

By 2023, Nuclear Power Plants (NPPs) produce around a quarter of the electricity consumed and about ½ of the zero carbon electricity in the EU having nuclear reactors in operation in 12 EU Member States: Belgium, Bulgaria, Czech Republic, Finland, France, Hungary, the Netherlands, Romania, Slovakia, Slovenia, Spain, and Sweden (World Nuclear Association, 2023; IAEA, 2023).

1.1. European nuclear E&T addressing an international concern

In the year 2000, the OECD-NEA published the report "Nuclear Education and Training: Cause for Concern?" which, for the first time, raised the awareness, at international level, of the common concern that nuclear fields might risk facing insufficient availability of human resources. The report clearly remarked that the Nuclear E&T were decreasing to challenging levels (OECD-NEA, 2000). This report recommended that governmental institutions engage in strategic energy planning, encompassing countries' education, manpower and infrastructure, and provide support for the development of "educational networks" connecting universities, research institutes and industry. Government, industry, universities, and research institutes were requested to work together to provide educational and research institutions with enough resources to offer attractive educational programmes, attract quality students and employees, and better attract the younger generation, to avoid the deterioration of nuclear education.

A regional movement started to join efforts and reinforce Nuclear E&T in Europe. Among the main institutions and different stakeholders around Europe, there was an appealing consensus about the identified common need of "Networks of Excellence and Integrated Projects" as the basis for the definition of the next EU nuclear research Strategy, and instruments for the implementation of Euratom research" (Van Goethem, 2004). On the EU Fifth Framework Programme (FP5) a new project was proposed by a group of European institutions; the project was entitled the "European Nuclear Engineering Network project", in short, the "ENEN project". One of its outcomes, the "European Nuclear Education [1]Network" (ENEN), was legally incorporated as the French association "Réseau Européen pour L'Enseignement des Sciences Nucléaires – ENEN", under the law of 1901, in October 2003 (Safieh et al., 2011a; De Regge, 2006; ENEN, 2019). This legal non-profit-making entity provided the partners of the ENEN project with an expected way forward to further continue the collaboration towards the instructive and scientific efforts set for.

Since then, the main objective of the ENEN Association has been the "preservation and further development of expertise in the nuclear fields by higher education and training". This objective is realized through the co-operation between universities, research organizations, regulatory bodies, the industry and any other organizations" (Safieh et al., 2011a; De Regge, 2006; ENEN, 2019). The ENEN statutes (ENEN, 2019) state that to meet with this objective, the ENEN Association promotes and develops collaboration in nuclear E&T, ensures the quality of nuclear E&T, and increases the attractiveness for engagement in the nuclear fields for students, researchers, and professionals. The creation of the ENEN association aimed to address the main risks and concerns raised by the OECD-NEA in 2000, with the main support of the European universities offering a master in Nuclear studies, and European nuclear research centers.

[1] Note the change of denomination from the intended "Engineering Network" as the project title was proposed, to the "Education Network" in the resulting association.

The development of these initiatives took place due to the support of the Euratom research and training programmes on nuclear reactor safety, while targeting the creation of a more homogeneous European research and the higher education area (Van Goethem, 2004).

The harmonization of the existing Nuclear Engineering curricula in the European Master of Science in Nuclear Engineering (EMSNE Certification) was achieved during the NEPTUNO Project (ENEN, 2005), where the bylaws were formally agreed (Moons et al., 2005) due to the continuous collaboration of the ENEN Association university members. Since then, this certificate has been delivered by the European Nuclear Education Network, endorsed by of all its members, to certify the highest quality standards of Nuclear Engineering Education and the European dimension (ENEN, 2019). Since then, more than 200 EMSNE certificates have been awarded (ENEN, 2022).

Despite the ongoing efforts, again in 2004 the OECD-NEA showcased the deterioration of the financial situation of research institutes, in many countries caused by the tough competition faced in the niche market where they operated, and the cuts suffered in their public funding (OECD-NEA, 2004).

Different initiatives were launched by the ENEN association between 2003 and 2006 (De Regge, 2006). Among them, similar master level approaches took place, such as the creation of European MSc Programs in Nuclear Sciences, the European MSc in Radiation Protection, the European MSc in Analytical Radiochemistry, and the European MSc in Radioecology, as supported by the EU-EURAC and EU-ENEN-II projects (Skipperud et al., 2010).

Collaborative approaches at national level were also launched. For example, the cooperation between the authorities and the nuclear power industry in Sweden was reported in the creation of the Swedish Centre for Nuclear Technology to assure nuclear safety education in the country (Löwenhielm and Lefvert, 2005).

In parallel, new initiatives in the same domain emerged from ENEN or were created in parallel with ENEN's support, such as: the creation of new projects and courses supporting research, e.g., the EUROTRANS project; the launch of new committees in ENEN; the launch of ANENT, i.e., the Asian Nuclear for Education in Nuclear Technology; the start of the World Nuclear University, and others reported by the EC in 2008 (European Commission, 2008).

ENEN served as example when the FuseNet project was first formulated. This project started in 2008, giving birth in 2010 to the European Fusion Education Network, FUSENET, with quite similar associative set-up and goals, but in nuclear fusion (Cardozo, 2013).

In 2008, the EC, concerned by the impact on safety, initiated a study titled "Nuclear Safety in a Situation of Fading Nuclear Experience" - which detailed the potential future lack of availability of key nuclear safety staff. Despite the initiatives at national and European level launched to address this problem, the number of students and graduates with a strong background in nuclear sciences would be insufficient to ensure safety functions in the future due to the difficulties to attract enough university graduates to these fields, and the difficulties of continuity of the education for the staff in the nuclear sector staff (European Commission, 2008).

In December 2008 the European Council welcomed the existence within the EU of "coordinated teaching and training leading to qualifications in the nuclear field, provided notably by the ENEN, and expressed its hope that, with assistance of the EU, the ENEN and its members will continue to develop the coordination of nuclear E&T in the EU" (Safieh et al., 2011).

In 2010, the SNETP, Sustainable Nuclear Energy Technology Platform (in the EU), reported efforts of improved practice in European countries, together with some international initiatives that had also proven effective, which could provide references for further development and optimization of nuclear E&T in the coming years (SNETP, 2010). During the early 2010s, Euratom E&T actions seemed to be experiencing a "nuclear renaissance" (Bhatnagar et al., 2011).

From 2009 to 2012, ENEN was involved in three FP7 European

Fission Training Scheme (EFTS) projects:

- ENEN III on nuclear engineering,
- PETRUS II on waste management
- ENETRAP II on radiation protection.

The ultimate objective of each EFTS project was to develop a European passport for training, using the European Credit system for Vocational Education and Training (ECVET) approach, which can be considered a portfolio of learning outcomes. Once established, the ECVET system is expected to be applied to other key training courses for achieving the harmonization of professional training over the EU countries (Safieh et al., 2011b).

In the year 2012, the OECD-NEA published the report "Nuclear Education and Training: From Concern to Capability" (OECD-NEA, 2012). It reviewed the initiatives that governments, educational and research institutes, and industry, from its member countries, had started during the decade (2000–2010). The same concerns remained alive because sustainable sources of skilled workers had not been achieved, neither in all areas, nor in all countries. A steady and sustainable supply of workers for the nuclear sector was considered a challenge because of the high level of competency required. The OECD –NEA issued recommendations for governments to continue stable engagement in human resource development planning for the long-term timescales, monitoring the demand and supply of human capacity, allocating necessary funds, supporting technical educational institutions and nuclear technology students, widening access to research facilities (including research reactors) for E&T purposes, and enhancing international co-ordination through educational networks so as to attract and retain high-caliber young professionals to secure industry and academic sustainability.

1.2. The diagnosis of the European Human Resources Observatory for Nuclear (EHRO-N)

In 2010, the EC launched the EHRO-N to provide some insight on the actual human resource levels needed in the nuclear industry. From 2010 to 2016, EHRO-N developed a series of reports evaluating the future demand of human resources needed for the nuclear industry in the EU. It started with a mapping of nuclear education possibilities and nuclear stakeholders in the 27 EU countries, i.e. EU-27, (Joint Research Centre, Lacal Molina M, Von Estorff U. M, 2013); and the supply and demand of nuclear experts studied for nuclear energy sector in the EU-27 (Joint Research Centre. Simonovska, V.; von Estorff, U., 2012). The subsequent European enlargement and integration of new countries was considered in an additional report (Joint Research Centre, Braunegger Guelich A, Von Estorff U., 2013).

A more detailed "Post-Fukushima Analysis of HR Supply and Demand" report (Joint Research Centre, Estorff, U., Brancucci, R., Flore, M., 2014) was made matching the plans presented in the Strategic Energy Technology Plan Study on Energy E&T in Europe (Joint Research Centre, Georgakaki, A., von Estorff, U., Peteves, S.D., 2014), providing the main source of data on enrolment of students in nuclear engineering in the EU countries. It was noted how the interest of younger generations in nuclear studies had decreased intensely, while many engineering faculties abandoned nuclear education. At the same time, the first generation of senior nuclear experts started to retire. The combination of these two effects has caused a gap between the incoming and the outgoing flows of talents into the European nuclear industry, research, and academia. If no immediate actions are taken, it is expected a shortage of qualified professionals in the near future, causing an increased risk of loss of valuable knowledge in the nuclear community. (Joint Research Centre, Estorff, U., Brancucci, R., Flore, M., 2014).

Several alternative demand scenarios (Joint Research Centre, Roelofs, F., Flore M., 2016) were studied, considering the influence of Long-Term Operation (Joint Research Centre, Roelofs F, Von Estorff U., 2013) and including an additional sensitivity analysis (Roelofs et al., 2016). The results of these reports showed that the current nuclear educational capacity in the EU would not be sufficient to provide the number of nuclear specialists needed for the long-term operation of nuclear power plants. This situation would be even more challenging to meet demand for nuclear talent if new construction projects were launched in the EU countries to achieve the 2050 decarbonization targets proposed by the EC. Therefore, the educational system in the EU would not be adequate to produce enough human resources for the nuclear sector, not only to preserve the existing workforce but also to meet some potential higher demand levels.

The risk still exists that without well-educated and trained personnel, safety and industrial capabilities and expertise in construction, operation and decommissioning of nuclear power plants are limited. The analysis and diagnosis made of the situation in the year 2000 (OECD-NEA, 2000) remain valid.

2. Nuclear Human Capacity Building (NHCB) in Europe

The term and concept of "Capacity Building" started being used at international level during the 1990s. It is widely used today in most of the international organizations, even though the capacity building practice needs to be defined within the context of each industry and organization.

2.1. The concept of nuclear capacity building

In the nuclear fields, the International Atomic Energy Agency (IAEA) is the intergovernmental forum for scientific and technical co-operation in the use of nuclear technology and nuclear power for peaceful purposes. The IAEA provides information and develops standards to ensure the safety and security of nuclear facilities (IAEA, 2006). For this purpose, all nuclear facilities and related organizations should have the required levels of competence in their human resources (IAEA, 2016).

The IAEA Capacity Building Concept was defined as a "systematic and integrated approach to develop and continuously improve the governmental, organizational and individual competencies and capabilities necessary for achieving a safe, secure and sustainable nuclear power programme" (Mallick & Molloy, 2014). In 2015, the IAEA published the "IAEA Report on Capacity Building for Nuclear Safety", as part of a series of reports on the lessons learned from the Fukushima Daiichi accident. The lessons learned for Capacity Building established the four essential elements of the umbrella approach for capacity building (IAEA, 2015a), including:

- Education and training;
- Human resource development;
- Knowledge management;
- Knowledge networks.

This four pillars and umbrella approach is a paramount concept for the institutions creating and maintaining nuclear expertise and knowledge around the world.

2.2. Challenges of NHCB in Europe

Having identified the potential shortage of nuclear expertise and the current and future demands of the nuclear industry and academia in the EU, numerous efforts were made to attract resources and enhance collaboration among universities, industry, and research centers to make nuclear studies and research more appealing in the region.

Despite these efforts, the number of students, researchers and professionals is still below the needs and expectations of the industry and educational centers.

The reasons for this stagnation in fostering the nuclear human capacity and supporting the nuclear E&T may be considered structural in the European region. However, some factors have been identified as

worth of consideration:

1. Different status of nuclear power programmes in the different countries in Europe, among which we can find ones that:
   - o operate a fleet of nuclear power plants,
   - o plan to build new plants,
   - o plan, are undergoing, or have undergone, the decommissioning of their nuclear reactors,
   - o have never had an operating nuclear power programme.
2. Variety of public credibility and acceptance across Europe:

It is necessary to properly communicate the scientific knowledge and gain trustworthiness and recognition about the sustainability benefits (ecological, economic, and social) of nuclear power in the de-carbonated energy mix with the general public and the decision makers. People's acceptance of nuclear energy is based on individual beliefs and perceptions, but it is also influenced by the institutional and socio-cultural context that each country faces (Wang and Kim, 2018). The nuclear academia still must dedicate efforts to use and foster both its public credibility and its competence, since other institutions devoted to nuclear training and operation have limited public credibility (Giot, 2017). Over-reliance on the proprietary industrial training or nuclearization of new talents may also, in the longer term, lead to less publicly available knowledge and may facilitate challenges with transparency and public acceptance (Cizelj et al., 2021).

3. There has been a weakly coordinated nuclear policy top-down approach:

   A lack of unified nuclear energy policy, driven by differing political stances among European countries, has led to challenges. There remains reluctance among a significant portion of the European society to recognize the benefits of fission nuclear energy. Public perception varies, with some countries phasing out or avoiding nuclear energy altogether. Notably, among the 27 EU member states, 14 do not produce nuclear electricity, while 13 operate nuclear reactors (Eurostat, 2021). Following the Fukushima disaster four countries (Belgium, Germany, Italy and Switzerland) opted to phase out or not to re-introduce nuclear power (Echavarri, 2013; Kristiansen et al., 2018).
4. A challenged balance between steady human resource supply by the national educational system and the reality of a cyclical demand caused by nuclear new build projects:

   The construction of nuclear power plants takes place in specific countries and locations over time. Simultaneously, the recruitment and development of human resources for nuclear operation and other organizations have historically occurred in waves. Between these waves, the demand of personnel development is limited. However, universities and nuclear departments produce, and therefore also require, a continuous flow of incoming talent to develop future professionals, researchers, and academics. If the support is not continuous over time the capacities and expertise risk to be lost (SNETP, 2021).
5. A weak bottom-up approach of diverse nuclear academic initiatives due to increased complexity: Many 'knowledge-type communities' have flourished through the decades of nuclear energy use in the EU. Many, but not all of them, have stemmed from, worked with, or approached ENEN for further cooperation and coordination. Niche-attractivity and increasing complexity of nuclear related communities started to be perceived in European efforts. The increasing complexity of the nuclear technology and the specific concerns and needs of E&T in particular fields made these communities to become more specialized overtime and more independent from each other as a result (SNETP, 2021).

According to Prof. Michel Giot's review presented in the NENE conference in 2017, the national organizations in charge of safety, together with the academic institutions providing nuclear science and engineering educational programmes have made a substantial contribution to the coordination, organization, and internationalization of the nuclear fission higher education in a somewhat unclear situation in Europe. Prof Giot added that since the EC has a limited area of competence regarding the related policies of its member states, it has been unable to propose a clear energy policy including the nuclear fission.

2.3. Quadrangular analysis model for NHCB scenarios analysis

Due to the varying status of nuclear energy programmes in the European region, various levels of nuclear human capacity development can also be found. To understand the different scenarios of capacity building that can be found in a specific region, it may be critical to understand the environmental conditions for the applicability of a model to sustain the nuclear human capacity in a region of the world.

Two factors that can be identified:

(A) the existence of a nuclear energy programme in the country. Are there operating nuclear power plants in the country or plans to build them?
(B) the existence of nuclear human capacity already developed in the country. Meaning the presence of a robust ecosystem of educational institutions and research centers, able to provide with human resource plans for the needs of the present and future nuclear activities in the country.

These two factors can be identified in a quadrangular diagram, being:

- In the horizonal axis - Factor A: Existence (or lack of) of a nuclear energy programme in the country.
- In the vertical axis - Factor B: Existence (or lack of) of nuclear human capacity developed in the country.

A quadrangular analysis model, Fig. 1, is proposed for the EU with these two factors conforming the Nuclear Human Capacity Building Quadrangular Analysis Model:

The following status for countries in the region can be identified and defined according to the 4 quadrangular areas:

- Status type 1: A country with No Nuclear Energy Programme and No Nuclear Human Capacity. This country in principle will not be the main target of capacity building activities. One may also note that almost none of the EU member states falls into this category at this time.
- Status type 2: A country with No Nuclear Human Capacity and a new Nuclear Energy Programme established. Any country willing to develop a new nuclear power programme, will develop its human resources as part of the comprehensive nuclear infrastructure development following the IAEA milestones approach (IAEA, 2015b).

The required nuclear capacity in the country will include lifecycle spanning human resource planning for the key nuclear organizations in the country, educational and research institutions with international-level academic excellence and a strong safety culture in all the involved institutions.

- Status type 3: A country with a Nuclear Energy Programme and Nuclear Human Capacity and Nuclear Energy. Countries with these conditions need to sustain their Human Capacity throughout the full lifecycle of their Nuclear Programme and, therefore, sustain its Nuclear E&T infrastructure. The country will need to maintain the high-quality level of educational and research institutions, the excellence

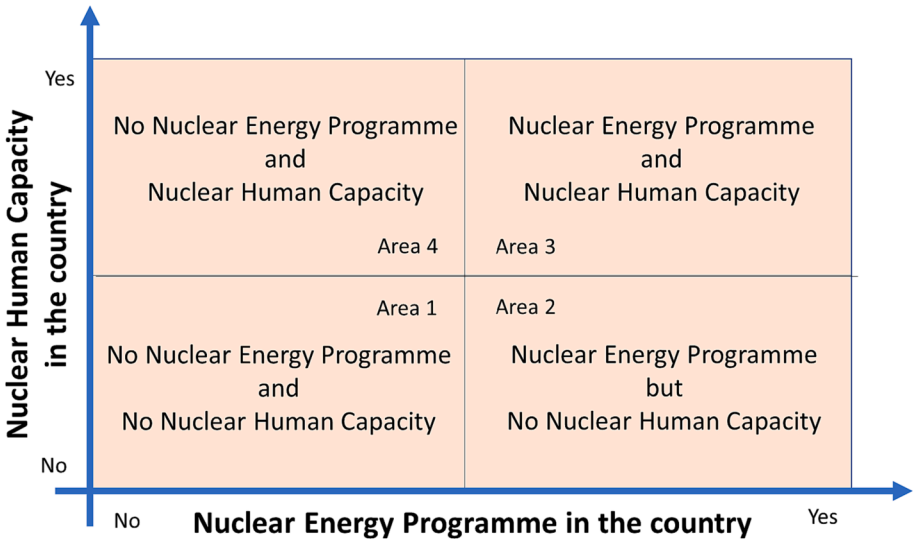

Fig. 1. Nuclear human capacity building quadrangular analysis model.

of their programmes, and the attraction of young talents to the nuclear fields.

- Status type 4: A country without a Nuclear Energy Programme and with Nuclear Human Capacity. Countries on these conditions may have already started or already transition to the decommissioning process of its nuclear programme. There is a possibility that the country may maintain its human capacity based on international activity.

The concern expressed by the OECD-NEA report raising awareness of the risk of Nuclear E&T activities decreasing to challenging levels while insufficient availability of human resources (OECD-NEA, 2000), can be displayed in the quadrangular analysis model by a country moving from status type 3 to status type 2 moving along the red arrow in Fig. 2. A country losing its Nuclear Human Capacity may face safety risks in the long term due to lower and unsatisfactory levels of competence in their human resources.

The focus of the European Nuclear Education Network aiming to preserve and further develop the existing European Nuclear Human Capacity can be framed within the quadrangular analysis model as sustaining the capacity of countries to remain as Status types 3 and 4, and avoid the risk of losing capacity and fall into Status type 2.

European efforts to build and sustain the regional Nuclear Human Capacity Building as per this Quadrangular Analysis Model can be framed in the area of countries willing to preserve status type 3. Only countries in areas 3 and 4 could support safe operation of existing and development of new nuclear technologies. These efforts are described as applied work in the following section.

3. Applied Work: Tackling different NHCB scenarios through coordinated E&T in the EU

As of today, in the EU, most of the coordination actions in these areas take place under the aegis of the Euratom programmes as part of the EU Framework Programmes for Research and Innovation.

Sustaining regional Nuclear Human Capacity Building entails strengthening and consolidating efforts and collaboration at the regional level with regional technological platforms, networks and coordinated projects in the areas of: Nuclear E&T, Human resources development, nuclear knowledge management and institutional networking. The ENEN has been recognized by most European stakeholders as the main institutional network in these areas.

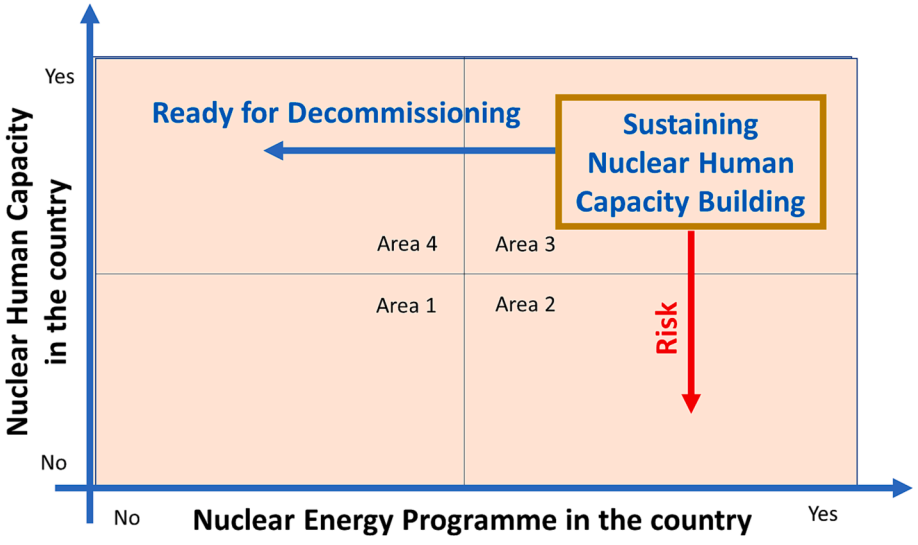

Fig. 2. Nuclear human capacity building sustainable strategy representation quadrangular analysis model.

The mission of ENEN conceived in 2003, with its projects and activities, provides to many institutional members and partners, as well as to individual students and professors throughout the EU and abroad, the possibility to collaborate and develop useful international relations, exchange ideas, develop E&T initiatives and create new areas of opportunity, often adverse to the studies in the nuclear fields (ENEN, 2019).

The following projects have been implemented or participated by ENEN on nuclear E&T, human resource development, knowledge management and knowledge networks topics in the EU since the year 2000:

Table 1 provides evidence on how the European nuclear E&T community operates, primarily, through the organization of European-funded projects. Public information about the content of these projects can be found on the CORDIS website (European Commission, 2022). The approval of funding for any of these projects follows a strict competitive process as public tender calls from the EC framework programmes and other EU agencies. Since the consortia to participate in these calls are freely proposed from the participating organizations, the strategy of the majority of these initiatives can be considered a "bottom-up" approach. This dynamic fosters a collaborative-competitive environment stemming from the technical leading organizations in each nuclear field.

3.1. Nuclear E&T projects and actions in the EU

Since 2003, the projects of the European Nuclear Education Network have been implemented initially to establish and develop the regional network and to establish specialized thematic communities of practice, specialized masters, and geographical collaboration beyond the EU.

3.1.1. Regional network development

The ENEN Project (Framework Programme 5, FP 5) "European Nuclear Engineering Network", aimed to produce a handbook, proposing a global network strategy, defining the major elements for a European network for nuclear engineering education and to perform pilot sessions on European nuclear education. The main outcome of the project was the creation of the ENEN (Safieh et al., 2011b).

The NEPTUNO Project (FP5) "Nuclear European Platform of Training and University Organizations" aimed to better integrate European E&T in nuclear engineering and safety to combat the decline in both student numbers and teaching establishments, thus providing the necessary competence and expertise for the continued safe use of nuclear energy and other uses of radiation in industry and medicine. Within this project, the European Master of Science in Nuclear Engineering (EMSNE) Certification was established and implemented (Moons et al., 2005).

The ENEN-II Project (FP6) "Consolidation of European Nuclear Education, Training and Knowledge Management" further developed ENEN Association in a sustainable way in the areas of nuclear engineering, radioprotection and radwaste management, including underground disposal. This approach recognized the multidisciplinary scope beyond the nuclear engineering, starting to host the interest and activities of the different nuclear communities (Safieh et al., 2011b).

Different training scheme projects ENEN-III, PETRUS-II and ENETRAP-II started under the 7th Framework programme of the EC. The ENEN III Project (FP7) "European Nuclear Education Network Training Schemes" covered the structuring, organization, coordination, and implementation of training schemes in cooperation with local, national, and international training organizations, to provide training to

Table 1
Summary of ENEN Nuclear E&T projects and activities in the EU since 2000.

	Framework Programme	Technical field	International	Education & Training	HRD	Knowledge Mgnt.	Knowledge Networks
ENEN Project	5	Nuclear Engineering	EU	ENEN	Courses	Capacity Mapping	ENEN
NEPTUNO Project	5	Nuclear Engineering	EU	EMSNE	Courses	Capacity Mapping	ENEN
ENEN-II Project	6	Nuclear Engineering	EU	Expansion	Courses	Capacity Mapping	ENEN
ENEN III Project	7	Nuclear Engineering	EU	Expansion	Courses	Several	ENEN
ENETRAP II Project	7	Radiation Prot	EU	community of practise	Radiation professional	Radiation Prot	community of practise
PETRUS II Project	7	Waste Mg & Geol	EU	community of practise	Waste Mgnt professional	Waste Mg & Geol	community of practise
PETRUS III Project	7	Waste Mg & Geol	EU	community of practise	Waste Mgnt professional	Waste Mg & Geol	community of practise
TRASNUSAFE Project	7	Safety culture	EU	community of practise	Safety Culture	Safety culture	community of practise
NUSHARE Project	7	Safety culture	EU	community of practise	Safety Culture	Safety culture	community of practise
CINCH Project	7	Radiochemistry	EU	community of practise	Radiochemistry	Radiochemistry	community of practise
MEET CINCH Project	H2020	Radiochemistry	EU	community of practise	Radiochemistry	Radiochemistry	community of practise
ELINDER Project	7	Decommisioning	EU	community of practise	Decommisioning	Decommisioning	community of practise
CORONA II Project	H2020	VVER	Russian Fed.	community of practise	VVER	VVER	community of practise
SECURE	HEUROPE	Medical Radionuclide	EU	community of practise	Medical Radionuclide	Medical Radionuclide	community of practise
PELGRIMM Project	7	Fuel R&D	EU	R&D	R&D	R&D	Support to R&D
FREDMANS Project	HEUROPE	Fuel R&D	EU	R&D	R&D	R&D	Support to R&D
GO-Viking Project	HEUROPE	Vibrations R&D	EU	R&D	R&D	R&D	Support to R&D
Tandem Project	HEUROPE	SMR R&D	EU	R&D	R&D	R&D	Support to R&D
OFFERR Project	HEUROPE	Facilities - R&D	EU	R&D	R&D	R&D	Support to R&D
ENEN-RU Project	7	Multiple	Russian Fed.	Mobility	Mobility	Curricula cooperation	Russian Fed.
ENEN RU II Project	7	Multiple	Russian Fed.	Mobility	Mobility	Curricula cooperation	Russian Fed.
ECNET Project	7	Multiple	China	Mobility	Mobility	International	China
EUJEP-2 Project	7	Multiple	Japan	Mobility	Mobility	International	Japan
EUJEP-2 Project	EACEA	Multiple	Japan	Mobility	Mobility	International	Japan
SARENA Project	EM	Nuclear Engineering	International	MSc Nuclear Energy	MSc & Mobility	MSc	EU Mobility
EIT InnoEnergy	EM	Nuclear Engineering	International	MSc Nuclear Energy	MSc & Mobility	MSc	EU Mobility
SATE Project	EM	Safeguards	International	Master on Safeguards	MSc & Mobility	MSc	EU Mobility
ANNETTE Project	H2020	Multiple	Multiple	Presential and MOOCs	Cross cutting	International	ENEN
ENEN PLUS Project	H2020	Multiple	Multiple	Access	Practical & Mobility	International	ENEN
ENEN2PLUS Project	HEUROPE	Multiple	Multiple	Access	Practical & Mobility	International	ENEN

professionals active in nuclear organizations or their contractors and subcontractors (Berkvens et al., 2015).

3.1.2. Thematic communities of practice

Through the following projects a large effort was made towards the harmonization and enforcement of education, training and information in radiation protection, nuclear and radio-chemistry and radioactive waste disposal.

Bringing together the efforts and resources of the radioactive waste communities, the PETRUS II Project (FP7) "Towards an European training market and professional qualification in Geological Disposal" enabled prospective and future professionals on radioactive waste management in the EU, whatever their initial disciplinary background, to follow a training programme on geological disposal which would be widely recognized across the EU. The PETRUS III Project (FP7) "Implementing Sustainable E&T Programmes in the field of Radioactive Waste Disposal" (CORDIS EU Research Results, 2016) aimed to strengthen the cooperative approach to E&T in the geological disposal with the purpose of expanding this cooperation between universities, waste management organizations, training organizations and research institutes efforts.

The MEET CINCH Project (H2020) "A Modular European Education and Training Concept in Nuclear and Radiochemistry" developed completely new E&T approaches based on remote teaching and the flipped classroom concept including and further developing material generated in the CINCH I and CINCH II projects, such as the NucWik platform and the remote controlled RoboLab experiments.

The ENETRAP II Project (FP7) "European Network for Education and Training in Radiation Protection – II" (CORDIS EU Research Results, 2013) aimed at developing a methodology for mutual recognition and setting up "reference" training schemes as an instrument to facilitate this mutual recognition, within the relevant regulatory framework. (Coeck et al., 2020).

The TRASNUSAFE Project (FP7) "Training Schemes on Nuclear Safety Culture" aimed to design, develop and test two relevant training schemes on Nuclear Safety Culture with a European dimension, based on a specific evaluation of the training needs (CORDIS EU Research Results, 2015). The NUSHARE Project (FP7) "Project for Sharing & Growing Nuclear Safety Culture Competence" focused on developing and implementing Education, Training, and Information (ETI) programmes aimed at strengthening safety culture for managers, decision makers and opinion leaders (Ambrosini et al., 2020).

The CORONA II Project (H2020) "Enhancement of training capabilities in VVER technology through establishment of VVER training academy" aimed to enhance the safety of nuclear installations through further improvement of the training capabilities aimed at building up the necessary personnel competencies. The development of a state-of-the-art regional training center VVER competence CORONA Academia was proposed (Ilieva et al., 2016; Geraskin et al., 2017).

The TOURR project joined efforts to develop a strategy for Research Reactors (RRs) in the EU and prepare the ground for its implementation in experiments necessary to develop commercial reactors, adaption and production of existing and new materials, including medical radioisotopes, and training programmes, focusing on both researchers and decision makers.

Finally, the ELINDER Project (coordinated by the EC Joint Research Centre) "European Learning Initiatives for Nuclear Decommissioning and Environmental Remediation" organized a set of complementary training courses on nuclear decommissioning and environmental remediation providing a common qualification.

3.1.3. Collaboration beyond the EU

The collaboration beyond the EU was organized with Japan and the Russian federation.

The collaboration with the Russian federation was based around the VVER technology with the ENEN-RU Project (FP7) "Cooperation with Russia in Nuclear Education, Training and Knowledge Management", which developed the framework of cooperation between the EU and the Russian Federation in terms of Nuclear E&T; and the ENEN RU II Project (FP7) "Strengthening of Cooperation and Exchange for Nuclear Education and Training between the EU and the Russian Federation" to develop a more permanent framework of cooperation between the EU and the Russian Federation in terms of Nuclear E&T.

With Japan, the collaboration focused on international exchanges with the EUJEP-1 project and most significantly the EUJEP-2 Project (FP7) "Post-Fukushima European Japanese Exchange Project in Nuclear Education and Training". Both projects promoted bilateral study/training programmes and internship mobility based on mutual recognition of periods of study and awarded credits and of existing E&T programmes in nuclear disciplines.

3.1.4. Special masters

The following Masters have been set up by consortia of collaborating universities, with regional institutional support, to create synergies and improved collaboration for improved and attractive new international curricula.

SARENA Project (ERASMUS MUNDUS) "Safe and Reliable Nuclear Applications"

This project proposed a two-year Master of Science in Nuclear Engineering, SARENA, aiming to develop scientific, technical and management skills enabling engineers to work in all domains related to nuclear energy and applications with a strong international culture, thus allowing students from around the world to join the programme (IMT Atlantique, 2022).

European Master's in Nuclear Energy (EMINE), by European Institute of Innovation and Technology – InnoEnergy

A two-year dual master's degree in energy engineering, innovation and entrepreneurship to teach future nuclear engineers how to address the key technical, social and environmental challenges faced by the industry today and in the future. It has been co-founded by a cluster of European universities and supported by the EU (EIT InnoEnergy, 2022).

SATE Project "Safeguards Training and Education"

The main goal of SaTE project is to provide a high-quality E&T program in the field of "nuclear safeguards", achieved by the development and implementation of a Nuclear Safeguards Master Program, short-term courses and tutoring training sessions (Politecnico Milano, 2022).

3.1.5. Collaboration among communities

The access to research infrastructures in nuclear fields has been supported by the EC, the GENTLE (Graduate and Executive Nuclear Training and Lifelong Education) project implemented Student Research Experiences (SREs) to facilitate access of European students to the EU countries' unique and specialized laboratories. Through the related accumulated experience, it has been identified relevant to elaborate a blended approach for the transnational access to infrastructures through mobility grants at pooled facilities within the different topical areas (Fazio et al., 2020).

In order to foster and develop the collaboration beyond the communities of practice established, the ENEN association launched "Advanced Networking for Nuclear Education and Training and Transfer of Expertise", ANNETTE Project (H2020). This project, Fig. 3, aimed at enhancing and networking the EU-wide efforts initiated in the past decades by different organizations belonging to academia, research centers and industry present challenges in preparing the European workforce in the different nuclear areas, paying special attention to continuous

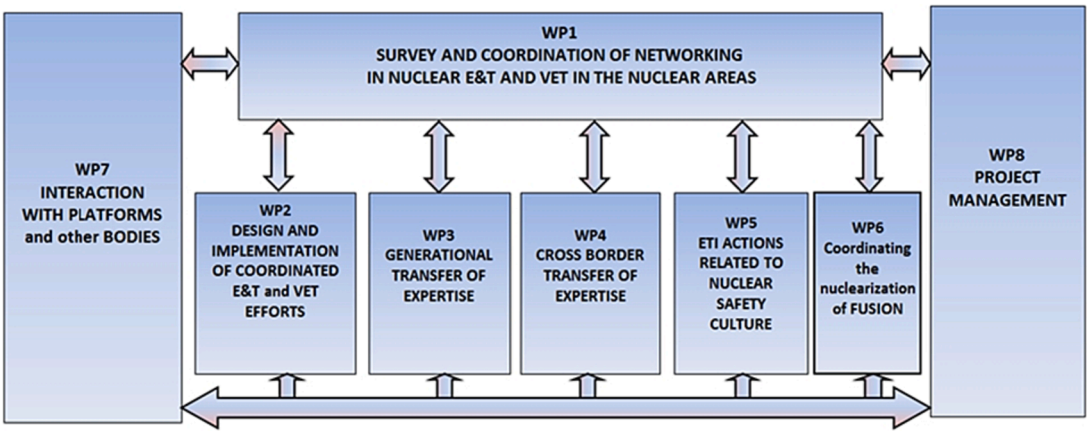

Fig. 3. Functional structure of the ANNETTE project, including links to fusion.

professional development, life-long learning and cross border mobility (Ambrosini et al., 2020). The ANNETTE project also analyzed the potential synergies between the Fission and Fusion domains, and the transfer of knowledge, and E&T experience with a working group devoted to the analysis of the nuclearization of Fusion (Ambrosini et al., 2018).

ENENplus Project (H2020) "Attract, Retain and Develop New Nuclear Talents Beyond Academic Curricula" (Cizelj et al., 2018; Pesznyak et al., 2018; Dieguez Porras et al., 2017). The primary motivation of the ENEN + project is being to substantially contribute to the revival of the interest of young generations in the careers in nuclear sector: attracting new talents, developing them beyond academic curricula, increasing the retention, involving nuclear stakeholders, and sustaining a revived interest for nuclear careers (Ambrosini et al., 2020). The ENENplus project also was recognized as a contributor to the revival of the interest in nuclear sciences for the medical physics community (Dimov et al., 2018). The strong cross border mobility program developed in the ENEN + project enabled more than 500 learners to gain more than 40 person years of the nuclear career enhancement experience in total.

As a result of the evolution of the activities of the ENEN Association and taking into consideration the efforts of collaboration among communities, such as the ENENplus project, this approach is contributing to the European strategic agenda for nuclear education, training and knowledge management (Cizelj et al., 2021).

3.2. *Evolution of projects portfolio*

The evolution of the portfolio of projects of ENEN, summarized in

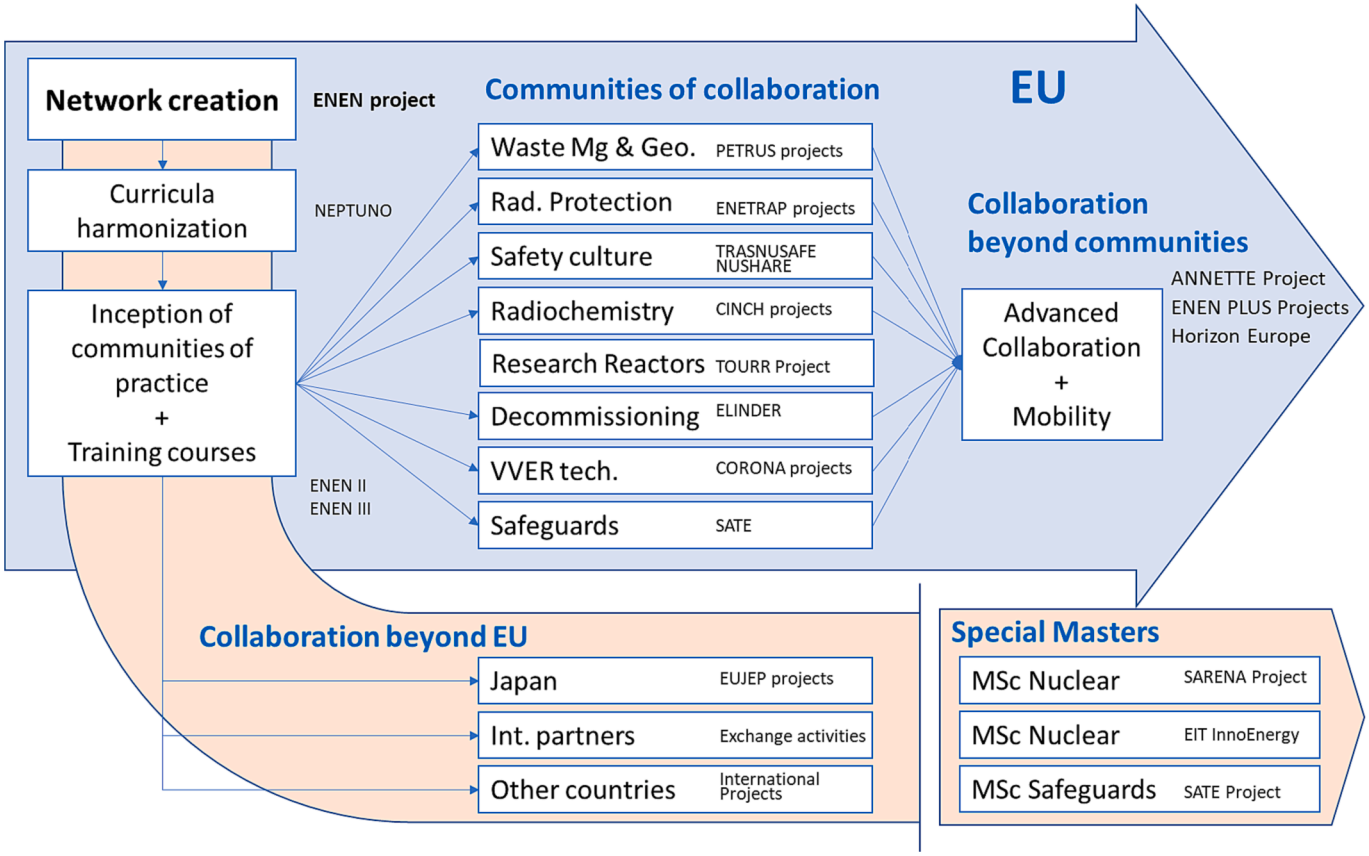

Fig. 4. Proposed visualization of the evolution of the portfolio of ETKM projects of the European Nuclear Education Network.

Fig. 4, shows an evolution from the initial development of the network (harmonization efforts) to the specialization per technical topic, into communities of practice or dedicated master, or by geographical area in the collaboration beyond EU.

Based on this past and current portfolio of activities and aiming to support future regional efforts in the EU a framework model to sustain NHCB regional cooperation is proposed.

Proposed NHCB regional collaboration framework model

In order to approach the internationally recognized challenge of the potential lack of availability of the human expertise in nuclear and the current and future demand and needs by the nuclear industry and academia, the adequacy and relevance of the Nuclear Human Capacity Building concept has been identified and developed. In this line, the NHCB quadrangular analysis model allows for the understanding of the different scenarios that a regions or countries may face in this regard.

A human centered and generic proposed NHCB regional collaboration framework model is presented in this section:

- The starting point for the development of the proposed model is the experience of the ENENplus project (Dieguez Porras et al., 2017) with a human centered approach along the lifecycle of the expert talent, i.e. “Attract, Develop, Retain and Sustain Talent”.
- This framework model is structured to allow for an understanding of the available tools and selected best practices, which are identified according to the internationally recognized standards in nuclear and proven successful implementation in the European region.

The particularities of the Euratom Treaty and the practice of its implementation through the Framework Programmes of the EC, and their interactions with the European Nuclear Education Network, have been the focal point on which this analysis has been based on. The concepts and tools used are in line with the standards and guidelines of the IAEA, due to its standard-like acceptance worldwide. The model can be contextualized to other different regions to allow for organizational efficiencies, smooth roll out of best practices and synergies with other initiatives.

Attract, develop, retain and sustain talent, a human centered approach

The human centered approach stems from the project ENENplus, launched to substantially foster the revival of the interest of new young generations in developing careers in nuclear the nuclear fields. Only through an engaging personal and professional development of the individuals entering in nuclear, the overall nuclear human capacity can be achieved and sustained. Therefore, the main work line of the project was structured along with the evolution of the individual, focusing on more experiential and attractive professional careers through academia and the industry. Accordingly, the main objectives were:

- Attract new talents to careers in nuclear;
- Develop the attracted talents beyond academic curricula;
- Increase the retention of attracted talents in nuclear careers;
- Involve the nuclear stakeholders within EU and beyond;
- Sustain the revived interest for nuclear careers.

In order to jointly address the needs of the different technical fields and communities of practice, the ENEN+ consortium (CORDIS EU Research Results, 2021) involved various nuclear stakeholders, including academia, industry, international organizations and technical support organizations, and focused on the learners and careers in the following nuclear disciplines:

- Nuclear reactor engineering and safety,
- Waste management and geological disposal,
- Radiation protection and
- Medical applications.

The ENENplus project, Fig. 5, organized Contests and Summer Schools at the level of the secondary school students and Bachelor students to test and showcase activities to make nuclear fields more attractive to young students. An attractive competition in European countries was organized where students competed and presented projects on nuclear topics at the national level and afterwards a Summer Camp was organized where students of national winner teams had the opportunity to be familiarized with nuclear applications and to discover nuclear careers. The main objective was to provide young people with complete, accurate and balanced information on nuclear energy and its applications. It has been observed a clear correlation between knowledge and support. Since large parts of the young public are unaware of the potential benefit of nuclear in their normal life (e.g., medical applications) and for future generations (e.g., carbon reduction and fight against climate change), a fortiori do not consider nuclear career as an option.

At bachelor level students had the opportunity to enroll in a mentoring program allowing to take benefit from academic support and career advising. Obtainment of internship in professional environments and getting financial supported by the ENENplus project was beneficial to students who had to choose their specialization after cross-disciplinary scientific studies.

Attracting non-nuclear workforce to nuclear fields was fostered following the ECVET methodology to assess training curricula specifically devised for the “Nuclearization” of professionals who had a formal E&T in a technical area outside the nuclear domain. A mobility fund was dedicated by the project to selected candidates.

The ENENplus project develop an innovative mobility scheme to facilitate access to infrastructures and participation in and from other Euratom research projects to enhance the experience and retention of PhD Students and post-docs. To widen the career perspective and better develop interaction between PhD students and industry, the project proposed the establishment of Doctoral Schools on Nuclear Innovation under the umbrella of ENEN Association.

The project also proposed to build solid networking bridges between different players acting for the improvement of the recruitment in nuclear sectors taking benefit from the presence of major industrial partners in the ENENplus project. Works included communication with industry and legislators, development of education, training and knowledge management strategy and facilitation of access to internships. ENENplus established a mobility fund of 1.000.000 EUR for European students, researchers and learners which was wholly utilized.

In 2022, based on the outcomes of the ENENplus project, the next ENEN2plus project (CORDIS EU Research results, 2022) was designed and launched as a large and integrative effort to include: a talent attention programme, actions for higher education, vocational education and training, a mobility program designed to support over 100 person-years of nuclear career-enhancing experiences, and a study of the EU supply and demand of nuclear human resources for power and non-power applications.

3.3. Proposed model for NHCB regional collaboration

The nuclear power sector has reached a critical juncture, where a significant challenge lies in the sustainable preservation of expertise and the effective management of knowledge and skills. This is essential for ensuring the highest level of safety and reliability over the long term (Yanev, 2013).

Therefore, a regional collaboration framework model for NHCB, Fig. 6, is proposed to support the regional coordination efforts in the EU aimed at sustaining and developing the nuclear human capacity building scientific ecosystem (universities, research centers, industry, technical

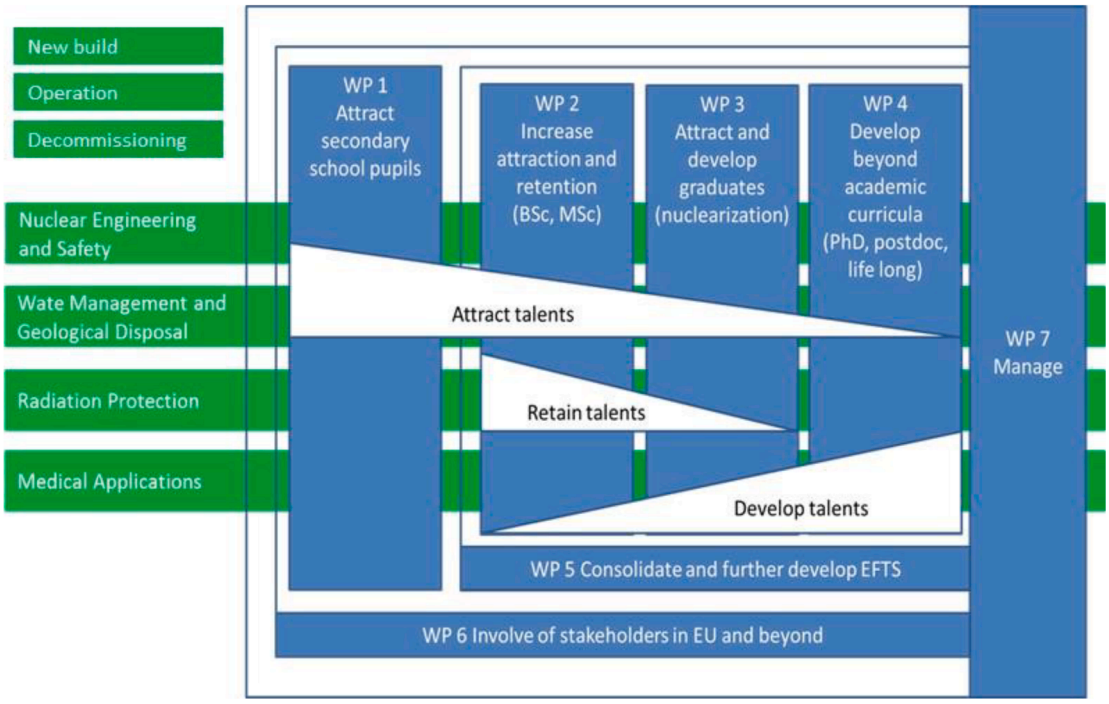

Fig. 5. Diagram of the ENENplus project (Dieguez Porras et al., 2017).

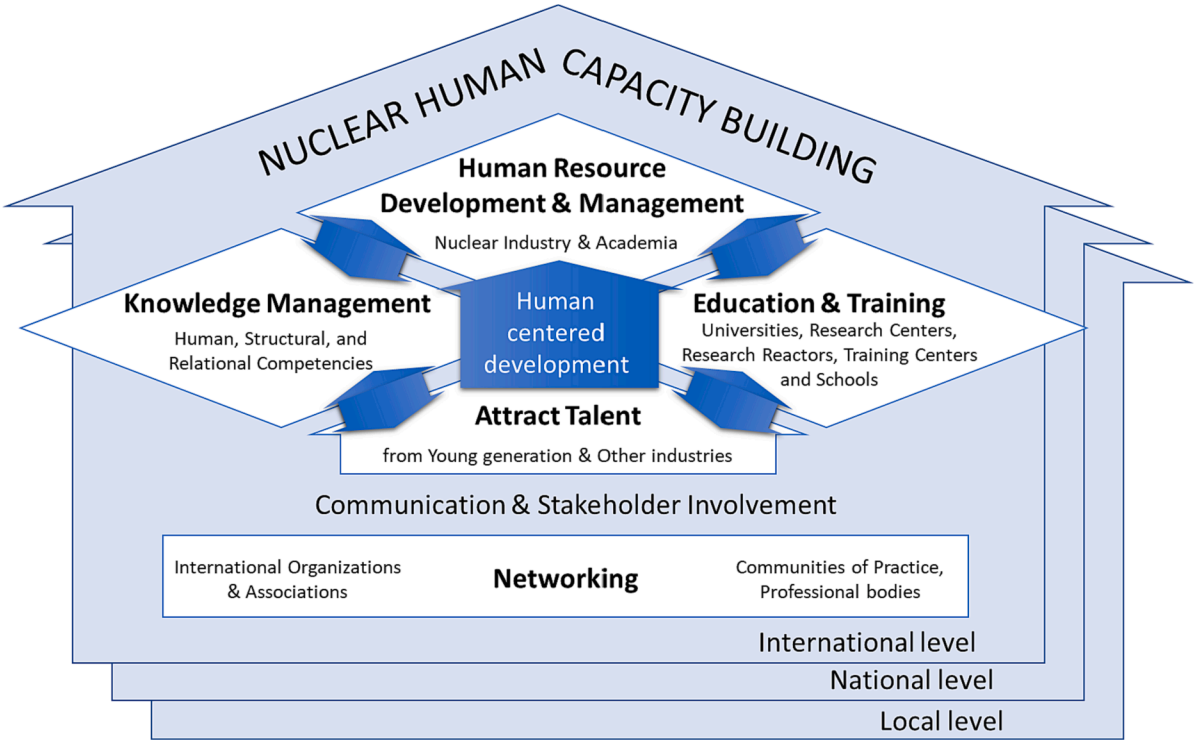

Fig. 6. Proposed regional collaboration framework model for Nuclear Human Capacity Building.

support organizations and regulators), the broader global nuclear community, and the needs of other industries where a similar applicability may be considered. Nuclear power has reached a breakpoint where the critical challenge will be maintaining competence and managing knowledge and skills in the long-term to guarantee safety and reliability at the highest level.

This regional collaboration framework model is proposed with the following pillars:

- Attracting talent from the younger generations into the nuclear studies, and professionals into nuclear sector careers, such as academia, industry, regulation, nuclear medicine, etc. This career path approach is inspired in the success of the ENENplus project

which aimed to address the initial concern identified in the OECD-NEA (2000) report.

- Focusing on individuals' professional careers, guided by a human-centered development approach, in developing talent through three foundational areas.:
  - o E&T activities implemented in universities, research centers, vocational schools, training centers, etc.
  - o Knowledge management, monitoring human, structural and relational competencies.
  - o Human resource development and management.
- Human resource development and management of the nuclear industry and academia to fulfill their needs of human talent and capacity. This is to be achieved by leveraging the relations with E&T institutions (universities and vocational schools) and their implementation activities, along with proper mapping and monitoring of their knowledge management needs and capacities.
- These elements of the NHCB are reinformed by purposeful networking efforts institutionalizing synergies among stakeholders through communities of practice, professional bodies, and associations.
- Communication and stakeholder involvement are critical elements to achieve success in every implemented effort.

All these elements and interrelations are implemented at the local, national and international levels. The local level approach may be particularly interesting when the effort aims to establish a local cluster of nuclear industry or academic institutions.

This proposed model aims to contribute to the development of a structured collaboration framework within the nuclear human capacity building ecosystem. It serves as a communication tool to support initiatives from governmental, public and private institutions in the European region, both top-down and bottom-up. The application of this framework should be contextualized adapted to the specific requirements of each situation, country, and region.

In this context, it is crucial to emphasize the significance of well-educated and trained personnel. Their absence presents significant challenges to the safe and effective conduct of nuclear scientific research and technology development. This concern is not just theoretical; the OECD-NEA (2000) highlighted that without such skilled personnel, the safety, industrial capabilities, and expertise essential for the construction, operation, and decommissioning of nuclear power plants may be limited.

Furthermore, this Nuclear Human Capacity Building framework model for regional collaboration may also be useful to other industries with specific talent attraction needs. The challenges and solutions for nuclear human capacity building also can be applied to other knowledge-based industries in high technologies, energy, and finance.

4. Conclusions

This work highlights the critical importance of preserving nuclear human capacity in Europe to maintain a robust pool of expertise and nuclear E&T infrastructure. The motivation and international context underpinning this need are also elaborated, emphasizing the relevance of the research.

The literature review chronicles the evolution of key concerns and actions to improve nuclear human capacity at the international level, with a particular focus on the EU. The OECD-NEA issued recommendations to strengthen the nuclear E&T and underscored the risks associated with knowledge and safety capability losses due to insufficient availability of human resources in the nuclear sector. Different European initiatives supported by the Euratom frameworks programmes helped maintain the E&T capacity in the region and raised policy awareness. Additionally, the EC launched the EHRO-N initiative to provide insight on the actual human resource levels needed in the nuclear industry in Europe, confirming these concerns.

The novel Nuclear Human Capacity Building Quadrangular Analysis Model has been introduced, designed to analyse and understand the various capacity building scenarios in Europe.

Moreover, the compilation of efforts at the regional level in Europe aimed at strengthening nuclear human capacity is presented. These efforts include projects, communities of practice, harmonization initiatives, and collaborative projects within the European nuclear ecosystem. These initiatives find the European Nuclear Education Network as the primary structured support, facilitating networking and collaboration in nuclear E&T in the EU.

Based on this experience and applied work in sustaining nuclear human capacity within the EU, a human-centered and generic NHCB Regional Collaboration Framework Model is proposed. This model aligns with internationally recognized standards and proven practices successfully implemented regionally. It serves as a tool for communicating, sharing, and presenting key elements essential for capacity building at the European regional level. Testing and contextualizing this model across different regions and industries, and in future projects is suggested.

Finally, the findings emphasize the critical role of well-educated and trained personnel in ensuring safe and effective nuclear scientific research and technology development, highlighting the significant challenges that arise in their absence.

CRediT authorship contribution statement

P. Dieguez Porras: Funding acquisition, Methodology, Writing – original draft. **J. Sanz:** Validation, Supervision. **L. Cizelj:** Funding acquisition, Validation, Writing – review & editing. **W. Ambrosini:** Funding acquisition, Validation, Writing – review & editing. **G. Pavel:** Validation.

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.

Disclaimer

Any views or opinions reflected in the article are those of the authors, expressed in a personal capacity, and do not represent necesarily those of their employers.

Data availability

No data was used for the research described in the article.

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