SNETP
Sustainable Nuclear Energy
Technology Platform

SNETP STRATEGIC RESEARCH AND INNOVATION AGENDA

July 2021

ABOUT US

The Sustainable Nuclear Energy Technology Platform (SNETP) was established in September 2007 as a R&D&I platform to support and promote the safe, reliable and efficient operation of Generation II, III and IV civil nuclear systems. Since May 2019, SNETP has been operating as an international non-profit association (INPA) under the Belgian law pursuing a networking and scientific goals. It is recognised as a European Technology and Innovation Platform (ETIP) by the European Commission.

The international membership base of the platform includes industrial actors, research and development organisations, academia, technical and safety organisations, SMEs as well as non-governmental bodies.

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FOREWORD
SNETP PRESIDENT

Climate change is a serious concern for Europe[1] and for the whole world. The current changes in our planet's climate are redrawing the world and magnifying the risks for instability in all forms.

The Intergovernmental Panel on Climate Change (IPCC) issued in October 2018 its Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. Based on scientific evidence, this demonstrates that human-induced global warming has already reached 1°C above preindustrial levels and is increasing at approximately 0.2°C per decade. Without stepping up international climate action, global average temperature increase could reach 2°C soon after 2060 and continue rising afterwards.

In line with the objective set by the Paris Agreement, more and more countries are making pledges to achieve "net-zero" emissions. In that context, the European Union demonstrated a strong leadership, setting the ambitious goal to be the first economy to reach carbon neutrality by 2050.

This decarbonisation effort is embodied in the European Green Deal[2] , the Recovery Plan for Europe[3] and a strong EU Industrial Strategy[4] designed to facilitate a more conducive environment for industrial ecosystems. Supporting jobs creation in the EU and strengthening the overall EU's resilience capacities are also part of this strategic policy direction set up by European Commission's initiatives.

In its "A Clean Planet for all" communication[5], the European Commission indicated that, along with a large share of renewable energy resources, nuclear energy would be part of the backbone of a low-carbon energy mix necessary to achieve carbon neutrality. This means that investment is needed in the nuclear sector, whether to prepare for a longer-term operation of existing facilities or to build new reactors, as presented in the latest "Nuclear Illustrative Programme" (PINC[6]) of the European Commission.

Technology has a key role to play in solving our

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[1] According to the Eurobarometer report on climate change, published in Sept. 2017, around three-quarters of European Union (EU) citizens (74%) consider climate change to be a very serious problem and more than nine in ten (92%) see it as a serious problem.

[2] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[3] https://ec.europa.eu/info/strategy/recovery-plan-europe_en

[4] https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/european-industrial-strategy_en

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0237

energy problems. However, no single option can address all outstanding issues. A broad portfolio of low-carbon energy sources and carriers needs to be investigated and developed as part of a general strategy to confront the growing problems faced not only here in Europe, but by the whole world. Electricity is going to take a growing role in this global perspective. Nuclear energy, as the largest single source of carbon-free and fully dispatchable electricity in Europe, certainly has a place in this strategy. The use of nuclear energy will not remain limited to electricity production only, nuclear energy can also play a significant role in decarbonizing other sectors through provision of heat to industrial processes or by production of hydrogen. At the same time, a realistic assessment of the potential of nuclear energy cannot ignore the essential question of public acceptance and proven economical competitiveness of new plants. Long-term sustainability, safety and global efficiency of operation and safe management of waste all influence the national investors and the general public's perception of nuclear as a viable energy source. This underlines the importance of innovative nuclear technology that promises economical competitiveness of new plants built on series, long-term operation of existing ones, vastly improved efficiency in the utilisation of natural resources, cogeneration of electricity, process heat and hydrogen, achieving even higher levels of safety, minimisation of waste and increased resistance to weapons proliferation.

Nuclear energy generation is a cross-cutting sector which uses and creates high level competences and high-level research facilities enabling the growth of the overall scientific and industrial capabilities of the European Union beyond the best international standards. Several nuclear projects have a cross sectorial potential as they are able to deliver data and results to other economic sectors of high interest to the European Research and Industry. In addition, Europe owns a strong nuclear industry and research community which is a key asset for the success of the Net zero goal, and its first step "fit for 55" by 2030, through these cross sectorial synergies in a globally balanced generation mix unifying Renewables and Nuclear Generation.

Within the framework of the Strategic Energy Technology Plan (SET-Plan), stakeholders have formulated a collective vision of the contribution which fission could make towards Europe's transition to a low-carbon energy mix by 2050, with the aim of integrating and expanding R&D capabilities in order to reach this objective.

With the aging of existing plants, European nuclear research and industry should be ready to deliver new facilities, big or small, that are able to provide a significant decarbonized and dispatchable electricity contribution to the European Grid in a time schedule compatible with the overall net zero objectives and also sustainable on the long run about fuel resources, waste management, heat and hydrogen generation.

The recent development of SMR ambition (small modular reactors) sets a new challenge for the nuclear industry in Europe.

The whole of these objectives is at the core of the Sustainable Nuclear Energy Technology Platform's (SNETP) shared vision, and its strategic research and innovation agenda (SRIA) that will enable this vision to be realised.

Since SNETP was founded in 2007, the organization has largely matured. The SNETP members and the members of its pillars decided in 2017 to pursue an evolution of the platform towards a legal association that has been officialised by a Belgian royal decree in September 2019. Over the years, SNETP has gathered more than 130 organisations and succeeded to promote collaboration between European partners coming from industry, research and safety organizations, and academia. With this, the role of nuclear fission in providing safe, reliable, and affordable electricity, with low greenhouse gas emission, has been reinforced. Such collaboration between experts is essential for assessing the maturity of nuclear technology, in its capability to continuously seek for improving safety and performance of the industrial installed base, while preparing the next nuclear generation and developing hydrogen generation and nuclear heat process application as well. SNETP has matured and confirms its viability in providing a forum for technical exchange, expertise, and joint undertaking in Research – Development and Innovation for nuclear fission.

The robustness of SNETP is founded on its three pillars: **NUGENIA** (Nuclear generation II and III Alliance), **ESNII** (European Sustainable Nuclear industrial initiative) and **NC2I** (Nuclear cogeneration industrial initiative) which have well-established programs and governance (thanks to dedicated EC funded projects) for succeeding in their missions on a balanced time line horizon. A deployment strategy[7] of its Strategic Research and innovation Agenda (SRIA) has been issued in 2015.

The success of SNETP, the unique platform will depend on a strong and bottom-up stakeholder involvement supported through a transparent and inclusive approach to membership of the platform itself and also on the support from the policy makers being at the national level or at the European union level.

I would like to thank the broad range of R&D&I stakeholders that have come together from industry, research centres, academia, technical support organisations and small and medium enterprises that took the challenge in updating the SNETP-SRIA over last years.

> ***Let's build the net zero future together!***

Bernard Salha

Chairman of SNETP
EDF Chief Technical Officer
Head of EDF Research and Development

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[7] http://www.snetp.eu

EXECUTIVE SUMMARY

Future of Nuclear Energy in Europe

The European Green Deal sets new and very ambitious goals for Europe: Becoming the world's first climate-neutral continent. This climate emergency is a huge challenge, but it is also a huge opportunity for our society and for European industry. Europe needs to speed up this historic transition, scaling up its 2030 greenhouse gas mitigation target to 55% and leveraging all available low-carbon options to fight climate change in the most cost-effective way. The European Commission is up to this task and SNETP is ready to deploy its ambitious vision and expertise.

To meet the CO2 emission reduction target in a cost-effective way, carbon emissions must have a price, and every sector will have to contribute. Such a framework will provide clarity and long term visibility to industries and citizens. This is why SNETP welcomes the Green Deal's broad ambition. The role that industry plays with research and innovation will be crucial. The energy transition is about investing massively in innovation and research, rethinking our economy and adapting our industrial policy.

In particular, new digital technologies will play a key role in a clean energy system. Using big data and artificial intelligence, electricity production has the potential to become more efficient and services can be tailored to specific needs. In this digital transformation, it is critical to protect all citizens and to respect consumers' freedom of choice and privacy. Huge investments in sustainable technologies and infrastructures are expected. According to recent studies €100 billion per year is needed just for clean power generation and storage. What some see as a cost, is actually an investment that will deliver growth and jobs.

As Europe moves away from fossil fuels, energy prices will be less driven by commodities and mainly driven by investments in renewables and carbon-neutral technologies. To lower capital costs and deliver timely investments, long term price signals and investment frameworks are needed. Predictable and meaningful CO2 prices, delivered by a resilient Emission Trading System market, are a key part of the equation. To ensure access to energy for all, and to offer a viable economic future to carbon-intensive regions and their workers, a just transition to a low-carbon economy needs to be ensured. The EU will have to provide a variety of funding that can be used to alleviate the socio-economic consequences on a much larger scale than today.

The direct use of electricity is the most energy-efficient and cost-effective way to decarbonize: the integration of transport, housing and energy sectors will make it possible to completely decarbonize the European economy if we can rely on CO2 free and affordable electricity. Above that, the direct use of process heat for heating or generation of energy-storing chemical substances would save a lot of energy when produced directly from nuclear heat. In Europe, more than 60% of electricity is already carbon-free. Electricity is intrinsically efficient. Today electricity covers about 20% of the EU's energy consumption but it is expected to reach 50-60% by 2050 taking into account the very significant energy efficiency efforts which are already underway. To reduce our carbon emissions further, we will need to rely on all competitive clean energy options. This includes renewables and nuclear in generation, efficiency, and storage, as well as smart grids and digital solutions.

Presently approximately three fifths of the European end users' energy is consumed via direct burning of fossil fuels for industrial heat needs, transportation and heating. Even if the electricity share rises significantly, a huge effort will remain to extend decarbonisation from electricity to the whole energy production in a majority of its sectors. In order to make progress on this line, it is crucial to cover other modes of fossil fuel consumption, and replace them by a combination of renewable sources and nuclear cogeneration. Nuclear cogeneration, even if not widely utilised today, is a mature technology, with a long history of R&D and generations of research reactors and is available at comparatively short notice.

SNETP regrets that, up till now, the European Commission has ignored nuclear power as a clean source of energy in its green recovery plan from the coronavirus pandemic. The EC's plan - Next Generation EU - aims to boost the EU budget with new financing raised on the financial markets for 2021-2024, and a reinforced long-term budget of the European Union for 2021-2027. Today the EU and the world are confronted by an unprecedented health and economic crisis, and responding to the COVID-19 pandemic is rightly the immediate priority for everyone. The energy sector across the EU, with nuclear energy at its core, continues to play an important role in that effort. Nuclear power plants are reliably maintaining essential power supplies, whilst ensuring the safety of employees, customers, the public and the environment.

26% of the electricity produced in the EU comes from nuclear energy and it remains the largest source of low-carbon electricity. However, 50% of the EU's electricity mix is still based on historic CO2-emitting fossil fuel technologies and these must be replaced by new low-carbon sources as the EU transitions to a carbon neutral economy by 2050. At the same time, additional power capacity will be required to meet growing power demand. The investment challenge is huge and the European Commission's strategic vision ('A Clean Planet for All') explicitly recognizes that nuclear, together with renewables, will form the backbone of the EU's carbon-free power sector in 2050. Today's deployed nuclear technology, coupled with further nuclear technology innovation, research and development (for example, in advanced and small modular reactors) is the perfect complement to renewables to deliver low-carbon electricity - 24 hours a day, 365 days a year. Nuclear can also be a significant contributor to district heating and low-carbon hydrogen production. In addition, it plays an indispensable role in the medical sector through diagnostic and therapeutic applications, detecting and curing cancer, and nuclear technology supports Europe's Beating Cancer Plan.

Member States have been clear that if they are to achieve their climate targets, a technology neutral approach will be essential. For some, any solution that excludes nuclear energy will be more expensive, less effective in delivering carbon reduction and will put at increased risk security of supply and system resilience. EU energy-intensive industries rely on stable, secure and affordable power supply to remain globally competitive and nuclear power is a key enabler. With thoughts across the EU turning to economic recovery and the need to rebuild economies after the pandemic, the commitment to addressing climate change has not wavered and will guide and shape recovery efforts. The energy sector will therefore continue to have a crucial role.

The European nuclear industry is ready and able to play its part, supporting national and EU clean, green economic revival by continuing to provide:

Growth, jobs (today the nuclear industry maintains 1.1 million direct and indirect jobs) and wealth creation at EU, national and regional level

Research keeping Europe at the forefront of innovation

Export growth potential

Progress towards a net zero economy, whilst maintaining full compliance with strict environmental regulations, including those related to nuclear waste.

> ***The energy transition is about investing massively in innovation and research, rethinking our economy and adapting our industrial policy.***

The nuclear sector is already an important industrial sector (more than 1.1 million skilled and localised jobs) in the EU and is strong across the full nuclear life cycle. There is now a growing awareness across the EU of the importance of preserving and enhancing industrial value chains and reducing over-dependency on third countries. The nuclear sector must therefore be part of the new, coherent EU industrial strategy. Life extension of the fleet is key to avoid an increase in emissions in the short term. Going forward, learning curves open up prospects to develop new nuclear at an affordable cost.

The nuclear sector provides:

- ✓ Consistency in policy development and implementation, providing clear signals that facilitate investment and enabling delivery of the required new, low-carbon nuclear power plants (large and small modular reactors), as well as maintaining the existing fleet, and enabling longer-term operation when appropriate;
- ✓ A science-based environmental assessment that delivers a prompt resolution of the nuclear energy position within the EU Taxonomy.

To sum up, the energy sector, with nuclear at its heart, is continuing to play a critical role powering the EU, delivering an essential low-carbon service to households and businesses in a safe, competitive and reliable way and keeping the economy moving. **Nuclear energy is an important contributor to all three main pillars of EU energy policy set out in the SET-plan and mentioned in the long term strategy document 'A clean planet for all' (EC, 2018): environmental sustainability, security of supply and economic competitiveness**. In addition, nuclear has one of the lowest life-cycle climate impacts of any energy source. Greenhouse gas emissions from the nuclear cycle on average are similar to those of wind power and only one quarter of the emissions of solar photovoltaics.

In addition, when compared with other sectors, the nuclear industry generates a very limited amount of waste. The average EU citizen generates about 1.4 tonnes of waste per year, of which 54kg is toxic waste and only 54g is classed as radioactive. Unlike other sectors, the nuclear industry takes great care to segregate and manage its waste safely, with dedicated funding set aside for its ultimate disposal. Because nuclear is energy-intensive, the area of land occupied by a nuclear power plant is, for example, less than one-hundredth of the area required for a wind farm of equivalent electrical output. Therefore it is the considered view of the SNETP members that **nuclear energy will play an important role in a clean, affordable and reliable future European energy mix alongside other low-carbon technologies**.

Nuclear energy currently provides a large fraction of low carbon power generation in the EU. It therefore plays an important role in efforts to decarbonize society and meet climate change targets. To continue this contribution and to reduce the burden on society associated with rapid development and deployment of new technologies in order to decarbonize society in the coming decades, R&D will reduce the costs of nuclear generation by optimising current operations and implementation technological innovations to reduce the capital costs of new capacity, improve the sustainability of nuclear generation and improve social and political acceptability, whilst adapting to changing conditions.

Within the decarbonisation pillar of the Energy Union and in accordance with Article 40 of the Euratom Treaty, in 2017 the Commission presented the latest nuclear illustrative programme (PINC). This provides an overview of developments and investments needed in the nuclear field in the EU for all steps of the nuclear lifecycle. It underlines that nuclear energy remains an important component in the energy mix in Europe with a 2050 horizon, as well as identifying some priority areas, such as solutions to continuously increase safety, improve cost-efficiency of nuclear power plants and enhance the cooperation among Member States in licensing new and existing nuclear power plants. The EU has also developed a legal framework for nuclear energy, ensuring that those Member States who chose nuclear are complying with the highest safety and security standards.

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nuclear power reactors were in operation in Europe in 2020

In 2020, 141 nuclear power reactors were in operation in Europe. New build projects are envisaged in more than 10 countries, with ten reactors already under construction in Finland, France, Hungary, the Ukraine, Slovakia, and the United Kingdom. Other projects are under licensing process, while projects in other countries (e.g. Bulgaria, the Czech Republic, Lithuania, Poland and Romania) are at different stages of preparation. On the other hand, some national energy policies have fixed a ceiling for the share of nuclear in their respective range of energy generation sources (e.g. France), others (e.g. Germany and Belgium) have decided to gradually phase-out from nuclear while other countries have never used nuclear energy. The benefits of nuclear energy are numerous, some of them are:

- Low-carbon, with low life-cycle emissions;
- Small land and resource footprint compared to other energy sources;
- Avoids pollution such as NOx, SOx, heavy metals and particulate matter;
- Provides continuous power, or can load follow if desired supporting peak and low demand;
- Increases resilience by decreasing vulnerability to extreme weather and external threats;
- Provides rotational inertia that helps to stabilize the grid and regulate frequency;
- Enables stockpiling of fuel, which boosts security of energy supply;
- Major employer in non-urban areas, supporting skilled hi-tech jobs and local economic activity;
- Can provide isotopes and support for research, medicine, industry and agriculture;
- Can enable decarbonisation of heat, industry and transport sectors.

This document presents the update of the strategic research and innovation agenda (SRIA 2021) of SNETP. Since 2013 (SRIA 2013), the EU-research in the nuclear field has allowed progress in various R&D fields and established a leading position worldwide thanks to the support provided by the Euratom Treaty. Many important programmes have moved forwards such as the MYRRHA experimental facility in Belgium. Other programmes have changed their orientation or timing such as the ASTRID programme in France and new initiatives have been launched such as the European Union High Temperature Experimental Reactor (EUTHER) by Poland to become a first of kind demonstrator for the high temperature gas reactor (HTGR) intending to substitute coal and imported natural gas to provide process heat to its chemical industry.

While maintaining the objective to address R&I challenges for nuclear fission technologies and priorities set by its members, this edition has adopted a new format. It aims to address the challenges faced by the nuclear fission in order to play its legitimate role in the European energy mix and to reflect the common challenges of the three pillars of SNETP (NUGENIA, ESNII, and NC2I), while maintaining the features of each. The document intends to provide a holistic SNETP view on the current agenda for strategic research and innovation identifying and presenting together:

- challenges ahead of the nuclear fission and R&D orientations to tackle them;
- specific challenges of each SNETP pillar and R&D priorities;
- cross-cutting challenges with common R&D orientations.

In fact, each pillar has a well-established programme and related reference documents. Common and specific challenges with respect to reactor technology are discussed with respect to operation and performance of the existing nuclear power plants, in-service inspection, qualification and non-destructive examination, design and demonstration of the next generation of fission reactors and small modular reactors (SMRs). Subsequently, enabling conditions like safety of nuclear power plants, development of fuel, assessment of the fuel cycle, management of spent-fuel, dismantling and decommissioning, strengthening social and environmental engagement, and the economic aspects are discussed.

Cross-cutting technologies, like digitalisation, modelling and simulation, and materials are also considered.

Last but not least, non-technological cross-cutting aspects such as research infrastructure, harmonisation and education, training and knowledge management are also taken into account.

Thus, this SRIA 2021 aims at shaping the programme of SNETP to maximise the benefit to society from the exploitation of nuclear fission as a low carbon, safe, flexible and competitive power source able to contribute significantly and positively reducing the impact of climate change.

Reactor Technology

Affordable, low carbon electricity supply is a critical enabler for a sustainable economic and social development. Nuclear power has played a key role in delivering such supply for decades in many countries and will continue to do so in the upcoming years as long as there is adequate evaluation and resolution of new challenges that are raised. **Therefore, optimum and efficient utilization of the existing portfolio of nuclear reactors is currently a necessity across Europe along with the integration of variable renewables in the electric grid.**

The current nuclear fleet was developed with plant design lives that were typically 30 or 40 years. The economics of nuclear are characterized by high capital costs followed by low and predictable operating costs, resulting from the low proportion of fuel cost in the total cost structure. This has enabled nuclear plants to supply reliable, competitive low-carbon baseload power. Continued optimisation of operations and innovation have enabled nuclear operators to achieve high plant capacity factors with a high degree of flexibility.

The importance of long-term operations is expected to increase in the coming years, and by 2030 the majority of the fleet would be operating beyond its original design life. Long-term operations are expected to represent the majority of nuclear investments in the short to medium term. Regulatory approval has been already granted for operational lifetime extension of certain nuclear power reactors in some Member States (e.g. Hungary and the Czech Republic). Decisions on operating lifetimes depend on current and forecast electricity market conditions and sometimes also on social and political factors. Such decisions are subject to a strict and comprehensive safety review by the competent independent national regulator, and as a basic requirement, the highest safety standards must be implemented.

License renewal of nuclear power plants has accelerated, allowing some plants to operate up to 60 years or more. As aging is an important issue, having an impact on the operation and maintenance costs, the nuclear industry has taken advantage of digital technologies to automate some of its testing and maintenance activities in order to reduce operation and maintenance costs.

The current and projected fleet of plants consists largely of water-cooled, water-moderated reactors. These reactors have over time achieved a high degree of maturity in terms of economic performance and safety. These reactors produce electricity in a reliable way without CO2 emissions. In fact, new build projects, based on light water technology designed for 60 years operation, are envisaged in ten Member States, with six reactors already under construction in Finland, France, UK and Slovakia. Other projects in Finland, Hungary and the United Kingdom, are under licensing process, while projects in other Member States (Bulgaria, the Czech Republic, Lithuania, Poland and Romania) are at different stages of preparation.

In addition, to achieve major steps in terms of sustainability (reduced high-level waste production, better use of resources and higher thermal efficiencies) and to open the way for high-temperature non-electricity applications, new types of reactors based on other coolant technologies are being developed alongside more effective and advanced fuel cycles as promoted by the GIF*. The use of fast reactors in a closed fuel cycle will allow a large increase in efficiency with regard to natural resources (uranium) consumption, by a factor of at least 50, leading to a more sustainable implementation of nuclear energy. One of the major concerns of society regarding the implementation of nuclear energy is also the high-level nuclear waste. Fast spectrum reactors with closed fuel cycles will allow a significant reduction in radiotoxicity and volume of high-level nuclear waste. Advanced reprocessing and fuel manufacturing techniques are needed to recycle the minor actinides in order to meet this goal.

Some advanced reactors are designed for non-electricity production as a potential application. Examples are hydrogen production, desalination of sea water and high-temperature heat applications. Reactors with a higher outlet temperature than current LWRs can address most needs of industrial steam supply, whilst applications at even higher temperature will be accessible for the future High Temperature Reactor (HTR). This has been outlined further and acknowledged by international organization in reports such as IEA (2018) and IAEA (2018).

There is an increasing interest in small modular reactors (SMRs) and their applications. SMRs are defined as power reactors up to 300 MWe, whose components and systems can be shop-fabricated and transported as modules to their designated sites for installation as demand arises. Several SMR designs adopt inherent passive safety features and are deployable either as a single or multi-module plant. The key driving forces of SMR development are fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil power plants, providing the opportunity of cogeneration, supplying energy to remote areas or developing countries with small electricity grids, and enabling hybrid energy systems integrating nuclear and renewables.

The small size offers potential advantages when compared to large power plants, in terms of design simplification and potential to use passive systems, increased resilience against external hazards and terroristic acts, as well as potential to reduce emergency preparedness zones. Through modularization, SMRs aim for economics of serial production and shorter construction time; this, along with the reduced capital investment per unit and faster generation of revenues from initial units while constructing the follow-up ones, is considered a key enabler for a significant decrease of the investment risk.

In the future, mini-nuclear reactors (very small SMRs) may also be a part of the new segmentation in terms of technical challenges and business opportunities. With rated powers between 0 and 30 MW, mini-reactors may reshape the nuclear industry, in order to compete with renewables as outlined by the European SmartGrids Technology Platform (2006).

With respect to reactor technology, the following main R&D&I priorities have been identified in the areas of construction, operation, in-service inspection, qualification and non-destructive examination, advanced reactors and the next generation, and small modular reactors:

01

CONSTRUCTION AND OPERATION

- Moving the approach for design practise from component based to system based;
- Identification, analysis, and countermeasures for ageing mechanisms together with development of monitoring systems and predictive tools for degradation in major components (metallic components, concrete structures, cables, …);
- Preventive and predictive maintenance and performance monitoring-based replacement / maintenance allowing reduction of costs and availability of the supply chain;
- Establish objective and comprehensive acceptance criteria for some degradation mechanisms;
- Development of risk-informed in-service inspection to all mechanical components;
- Understanding the technical (or other) barriers that preclude the transport of qualifications between countries and finding methods or procedures on how to overcome these;
- Verification of the accuracy of non-destructive testing inspection simulation software;
- Explore new non-destructive methods for plant-condition monitoring and health system monitoring.

02

ADVANCED REACTORS AND THE NEXT GENERATION

- Fuel and materials development and qualification;
- Improved understanding of coolant behaviour, thermal hydraulics and chemistry control;
- Component design and testing;
- Development of appropriate instrumentation and reactor/system control;
- Safety assessment and code validation;
- Fuel handling technology and fuel-coolant interaction;
- Robust decay heat removal systems;
- Development of out-of-pile and in-pile mock-ups and demonstrators.

SMR

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- Safety assessment of existing concepts: Feasibility and benefit of inherent safety features (e.g. natural convection cooling and passive decay heat removal);
- Review of safety classification of components;
- Development and qualification of components (e.g. compact heat exchangers) and associated fabrication processes;
- Human factors when employing multi-module SMR plants monitored in a single control room or remotely;
- Cost reduction through Design simplification, compactness, and modularity;
- Advanced manufacturing, assembly and digitalisation of processes;
- Economics and Financing (e.g. effect of in-series production on affordability, required threshold for orders, analysis of financing options);
- Site availability (water vs. air-cooling);
- Licensing (standardization and simplification);
- Acceptance of modularity aspects;
- Hybrid Energy Systems, hydrogen production, energy buffering/storage and cogeneration;
- Facilitation of demonstration.

Enabling Conditions

The safety of nuclear installations has been a priority since the beginning of nuclear reactor design and deployment. It is well recognized that an accident in any country in any part of the world affects the nuclear sector globally, therefore learning from the past events and collaborating between all stakeholders worldwide has become an asset of the nuclear community. In fact, during the nearly 80 years of designing, construction and operation of research reactors and commercial nuclear power plants, the concept of nuclear safety has been collaboratively developed to provide protection against a wide range of potential hazards with defence-in-depth and providing resilient safeguards. Nuclear safety remains the top priority for sustainable nuclear power plant operation, and therefore SNETP puts emphasis on R&D&I activities to continuously improve safety of plants, by understanding accident phenomenology and developing methods for safety and risk assessment. Therefore, support of nuclear safety programs and harmonisation of approaches to nuclear safety is an important aspect of nuclear safety effort worldwide and especially in Europe following the European safety directive (ref).

> ***Nuclear safety remains the top priority for sustainable nuclear power plant operation.***

It should be remembered that nuclear facilities are designed, constructed, operated and maintained for safe and reliable operation in accordance with high-level principles, requirements and concepts (e.g. Defence-in-Depth) and their safety may not be jeopardized by a single failure, human error or a combination of these. To ensure this, a nuclear facility design shall apply the concepts of diversity, redundancy, physical separation and functional independence throughout the lifetime of the facility. This requires the timely implementation of preventive and predictive maintenance of the nuclear facility by the use of modern Structures, systems and components (SSCs) of high quality and proven reliability, functioning when needed, from different and best available sources, including suppliers that offer and prefer producing SSCs according to non-nuclear industry standards or alternative nuclear codes and standards.

Nuclear fuel production and use in commercial reactors have reached a relatively mature state. Research on fuel behaviour mechanisms with the help of in-situ experiments and computational codes is focused on both normal operation and accidental conditions, performed experimentally and with simulation models.

Fuel treatment, transportation and interim storage (spent-fuel management) research satisfies the need to fully understand the challenges faced by managing the extended storage periods of the spent-fuel and their storage systems following reactor utilization, provide confirmation of the condition of stored fuel and storage systems and optimize the fuel management options. Management activities, include handling of the spent-fuel, associated diagnostics, storage in spent-fuel pools at power plants, transport, drying of fuel, interim storage in either wet or dry conditions before either reprocessing and recycling, or transfer for final disposal, are being pursued with a higher degree of innovation and collaboration.

For light water reactors, the most commonly adopted fuel cycles are the open fuel cycle, with final direct disposal in geological repositories, or mono-recycling of plutonium, via the production and storage of MOX fuel pending future recycling. Fuel cycle sustainability, in terms of resource utilisation and high level waste minimisation, can be substantially improved using closed fuel cycle strategy with fast reactors. In addition to the development of fast nuclear reactors, R&D is required to develop more radiation tolerant processes that support the separation of long-lived minor actinides, multi-recycling processes, and associated fuel fabrication processes. Qualification of modified fuels is also required alongside with their impact on spent fuel management and disposal systems. Such R&D is necessary to significantly reduce the long-term uranium consumption, making the present reserves last for several thousand years, and reduce the long-term radiotoxic inventory by more than a factor of 100 and reduce the repository heat load by more than a factor of 10, depending on geology. Because of the large reserves and currently low prices of uranium, several countries (France, US, UK) expect that the need for deployment of closed fuel cycles with fast reactors will arise only by the end of the 21st century, whereas other countries pursue a more aggressive approach towards technology leadership (Russia, China, India).

Decommissioning and Waste management covers the management, treatment and disposal of waste arising from operations across the nuclear fuel cycle. Importantly, it also considers waste minimisation and recycling of non-fuel materials. The focus should be on the identification of best practices from the international community and the development of innovative technologies and methods that will reduce decommissioning costs and timescale, thereby also improving safety and enhancing environmental performance.

With respect to enabling conditions, the following main R&D topics have been identified in the areas of safety of nuclear power plants: development of fuel, the fuel cycle and spent-fuel management; dismantling and decommissioning; and social, environmental and economic aspects:

> ***SNETP puts emphasis on R&D&I activities to continuously improve safety of plants, by understanding accident phenomenology and developing methods for safety and risk assessment.***

01

SAFETY ASSESSMENT OF NUCLEAR FACILITIES

- Assessment and mitigation of external hazards especially those beyond design basis (e.g. flooding);
- Identification and quantification of uncertainties within the assessment methods and on the local measurements;
- Improve the robustness of the methods dealing with source identification and cumulative hazards;
- Development of methodologies extending the scope of existing probabilistic safety assessment, in particular to take into account inherent safety features;
- Focus on long-term and multi-unit loss of safety functions;
- Development and validation of advanced tools and methods for deterministic and probabilistic safety analysis;
- Integration of new equipment in power plants (converters, vacuum circuit-breakers, etc.) and evaluation of their impact and reduction of the stresses they may generate;
- Support operation of remaining European experimental facilities;
- Safety and reliability assessment of the capability of passive safety systems and inherent safety features to perform the assigned function;
- Methodology for the reliability evaluation of digital instrumentation and control systems and its integration into probabilistic safety assessment;
- The ability to cool in- and ex-vessel corium/debris;
- Mitigation of gas explosion risk in containment;
- Source term assessment and mitigation;
- Accidents in spent-fuel pools.

02

FUEL DEVELOPMENT, THE FUEL CYCLE AND SPENT-FUEL MANAGEMENT

- Development of advanced fuel designs with focus on safety and economics (Accident Tolerant Fuel, high burn-up and enrichment);
- Improvements in assembly design and manufacturing with focus on reliability, robustness and economics;
- Development of new fuel manufacturing capabilities and transport solutions for ensuring Security of Supply and independency of Europe supply chain;
- Improvement of manufacturing quality control technologies;
- Improvement and validation of predictive fuel performance and safety tools;
- Improvement of post-irradiation examination (PIE) methods;
- Ensuring availability of key experimental facilities (research reactors, hot cells and laboratories, mechanical and thermal-hydraulic test facilities);
- Improved understanding and optimisation of temporary spent-fuel storage system behaviour;
- Integration of spent fuel management and disposal for open cycles.

03

DECOMMISSIONING, DISMANTLING & WASTE MANAGEMENT

- Minimisation of waste production by design, material selection, operational measures, efficient dismantling technologies, and development of advanced waste treatment and conditioning technologies;
- Development of characterization techniques for waste inventory assessment and plant and facility assessment;
- Development of new technologies and approaches to deliver decommissioning safer, cheaper, faster and sustainable, to enhance waste treatment processes, and to minimize waste arising, through design, operation and decommissioning.

04

SOCIAL, ENVIRONMENTAL AND ECONOMIC ASPECTS

- Societal impact on the functioning of the production means (densification of territories, water management, etc.);
- Deterministic and probabilistic safety assessments for increasing availability factors and enabling optimisation of safety margins and power uprates;
- Creation of a pan-European communication campaign allowing citizens to educate themselves;
- Analyses of the impact of intermittent external loads including grid disturbances on safety functions and life expectancy of existing and new nuclear power plants;
- Optimisation of the operation of hybrid systems combining different types of energy (electricity and heat) sources (nuclear, fossil fuel-fired plants, renewables) and different types of energy storage (heat, hydraulic, hydrogen...);
- Analyses of the impact of new hazards (e.g. drone attacks, stuxnet viruses) on safety functions of nuclear power plants.

Cross-cutting technologies

Cross-cutting technological topics like materials, monitoring tools, digitalization of systems and process, modelling and simulation of multi-physical and multiscale phenomena are essential for progress in the nuclear field from licensing to decommissioning through life long operation. Digital technology is an essential tool for increasing the safety and competitiveness of the nuclear industry as it is for other industrial sectors such as aerospace or automotive. All the three SNETP pillars are involved in this digital transformation. The main objective of digitalisation, modelling and simulation is to continuously increase safety and competitiveness for the operation and maintenance of existing nuclear power plants and for new build. It will also enable improved cooperation between partners of the nuclear sector.

Developments in the field of modelling and simulation have three goals.

✓ The first is to adapt and accelerate the coupling between existing calculation codes by improving interoperability in order to provide a more complete understanding of complex, inter-related phenomena (including data analytics, artificial intelligence, ...);

✓ The second goal is to unify numerical applications and make them consistent by linking the world of advanced expertise studies and industrial modelling (including Digital Twins);

✓ The third goal is to benefit from breakthroughs in advanced visualisation technologies (including virtual reality and augmented reality).

Research and development on structural materials is important for both operational reactors and future reactors. A deeper knowledge of the materials used in the reactor plants currently in use allows to estimate and predict the residual life with greater precision and to assess the degree of reliability of components all along their lifetime.

Regarding the new reactor concepts, the availability of new materials more resistant to neutron damage, to high temperatures and to the aggressiveness of non-moderating coolants, is necessary to deploy advanced reactors.

With respect to cross-cutting technologies, the following main R&D topics have been identified in the areas of digitalisation, modelling and simulation, and materials:

01

DIGITALISATION, MODELLING AND SIMULATION

- Development and validation of multi-scale, multi-physics, and multi-phase analysis tools including uncertainty quantification methodologies;
- Development of methodologies to ensure digital continuity over the complete life-cycle;
- Integration of cybersecurity in the digitalization process;
- Digital Twins of components and systems up to the entire installation.

02

MATERIALS

- Advanced manufacturing in a broad spectrum methods;
- Understanding physical mechanisms and development of relevant models;
- Materials with better resistance to high temperature and corrosion with or without simultaneous irradiation;
- Methodologies related with materials qualification, especially of welds and joints, internal stresses evaluations and online monitoring;
- Development of non-destructive, non-intrusive methods to monitor the health of components during their whole lifetime;
- The use and maintenance of nuclear material testing infrastructures.

Cross-cutting Aspects

Many cross cutting non-technological aspects play an important role in the progress of nuclear energy. A few examples are:

1. **The availability of state-of-the-art research infrastructure** (in particular for materials and fuels research, innovation and nuclear safety). Key infrastructure elements are irradiation facilities, hot cells and transport routes. Current initiatives in France with the Jules Horowitz Reactor, in Belgium with the MYRRHA initiative, and in the Netherlands with the PALLAS reactor are complementary and essential to renewing European irradiation facility infrastructures for the coming decades and to provide important non-power related nuclear services for medical and industrial applications. Political and financial support is needed to realise these capital-intensive projects. Current-day models do not sufficiently account for the increasing costs imposed by security and waste handling, endangering access and availability of these infrastructures, amongst others. Therefore, further work is planned to establish a financially sound basis for the operation of such infrastructures.
2. **Ensuring consistency of components, tools, and safety standards**, which will be a prerequisite for the cost-effective deployment of new nuclear reactors in Europe. This endeavour requests vendors and suppliers to engage in an initiative to standardise their components and codes to a higher degree in order to ensure a faster procurement process, higher compatibility, and more transparent and higher safety standards, and knowledge management. Among them, the most challenging task is

harmonization of safety standards. Because nuclear safety is a national responsibility, national regulators are independent, leading to different sets of safety rules in the EU. It is not widely appreciated yet, although substantial effort is being made by WENRA, ENSREG and ETSON and IAEA, that independence of judgement does not exclude cooperation on harmonised safety standards.

3. **Education, training and knowledge management** are vital to provide a competent, skillful and sufficiently long-term workforce to deliver a nuclear energy programme and to provide reliable advice to policy making bodies. This requires cooperation between universities, industry, regulators, and governmental bodies to ensure the required quality and quantity of the workforce from inception of a nuclear program to completion of remediation and disposal activities.

The following main R&D priorities have been identified in the areas of research infrastructure, harmonisation, and education, training and knowledge management:

01

RESEARCH INFRASTRUCTURES

- Critical assessment of EU-research infrastructure in terms of availability, functionality, and adequacy with the R&D&I priorities and industrial needs, e.g. IAEA;
- Creation of a financially sound basis for the operation and maintenance of this infrastructure;
- Support of trans-national access to these facilities by implementing cost effective access to the experimental facilities.

02

HARMONISATION

- Enable wide and general use of non-nuclear industry standard components and equipment (manufactured according to ISO, EN, etc.) in nuclear facilities, in particular for SSCs of lower safety class (SC3), without any additional nuclear specific requirements, providing (a) the components and equipment have a proven record of high quality and functionality, (b) they are subject to additional qualification tests to meet environmental and seismic requirements as appropriate and (c) they undergo a dedication process that provides reasonable assurance that they deliver their intended safety function;
- Allow the use of safety related SSCs produced according to alternative nuclear codes and standards, meaning nuclear codes and standards that are different to the ones that are normally used in the country that hosts the nuclear facility;
- Common licensing rules and procedures of new technologies;
- Common Regulations and standards at the EU level.

03

EDUCATION, TRAINING AND KNOWLEDGE MANAGEMENT

- Development of multi-disciplinary knowledge and skills;
- Steady education and training, and retention of talented and skilled workers;
- Safeguard, aggregate, and disseminate Euratom scientific and technical knowledge on nuclear fission;
- Establishment of a fair energy educational framework in elementary and secondary schools.

Conclusions and Way Forward

Multiple forecast studies indicate that the world, and Europe in particular, will need nuclear fission energy in its energy mix to enable a rapid and cost-efficient transition to a low-carbon society and to minimise the effects of climate change. SNETP's vision aligns with this understanding. Its recent transformation into a legal international association integrating all fission technologies and promoting the collaboration between more than 130 members from Industry, research centres, academia, technical support organisation and small and medium enterprises, enables it to formulate and deliver technological innovations required to maximise the contribution of nuclear power production to achieve this goal.

This updated Strategic Research and Innovation Agenda sets out R&D priorities that support optimisation of the current nuclear fleet and the development of innovative technologies to substantially reduce the financial costs and maximise the environmental benefit of nuclear energy from now to the medium and long term. While this agenda is aligning with the long-term vision of SNETP it is adapting at the same time to the changing landscape and is taking account of progress and trends in research and innovation methods, tools, and knowledge.

> ***The world, and Europe in particular will need nuclear fission energy in its energy mix to enable a rapid and cost-efficient transition to a low-carbon society and to minimise the effects of climate change.***

The Strategic Research and Innovation Agenda also provides valuable underpinning of commercial nuclear service delivery by EU organisations in other countries, bringing financial benefits to European society. SNETP continues its commitment to factually inform the public about the benefits and challenges of nuclear energy. To this end SNETP develops relationships with international/European and national organizations like IAEA, OECD/NEA, WANO, INPRO, GIF WNA, Foratom, WENRA, ENSREG, WENRA, ETSON …. in addition to the European commission services.

While safety will always remain a first principle in nuclear research, this update of the Strategic Research and Innovation Agenda emphasizes that research towards affordability, reliability and financial risk mitigation is a requirement for long-term operation and future deployment of nuclear systems. After all, without long-term operation and new nuclear deployment in Europe, we will not be able to meet the environmental goals set in international agreements. The current Strategic Research and Innovation Agenda has been aligned with the Strategic Energy Technology (SET) Key Action 10 Implementation Plan, with the European Green Deal plan as well as with the goal of carbon-neutral EU by 2050. It also includes the vision of the three SNETP pillars, NUGENIA, ESNII, and NC2I.

> ***Research towards affordability, reliability and financial risk mitigation is a requirement for long-term operation and future deployment of nuclear systems.***

The future for development and deployment of nuclear technology in Europe is bright if we manage to:

- Operate our assets in a reliable, affordable, and safe way;
- Reduce capital and operational costs through innovation;
- Extend the use of nuclear energy to non-electricity sectors, in particular to the provision of heat for industrial and chemical processes, and the production of CO2-neutral fuels for transportation;
- Develop break-through technologies to improve competitiveness, safety and sustainability;
- Communicate in an effective way the benefits of nuclear energy to European citizens and policy makers to create the conditions for nuclear energy to support society's climate change and competitive aspirations;
- Continue to invest in the facilities and workforce needed to deliver these objectives;
- Work effectively with international organisations to leverage European knowledge and skills;
- Connect scientists and reactor designers, operators, and vendors (to ensure we are working on the right challenges);
- Link experimental teams with numerical modellers (to ensure mutual knowledge exchange improving both sides of the scientific spectrum).

Clearly, the speed of innovation and responsiveness of this sector depends on the funding available to drive innovation. Funding mechanisms put forward by the European Commission, e.g. through Horizon Europe, but also industrial and national initiatives will play an important role in which SNETP may act as a catalyser to encourage collaboration and maximise integration of research, development, and innovation efforts.

While safety will always remain the top priority for nuclear research, this update of the Strategic Research and Innovation Agenda emphasizes that research towards affordability, reliability and financial risk mitigation is a requirement for long-term operation and future deployment of nuclear systems. In the view of SNETP, only with long-term operation and new nuclear deployment, will Europe be able to meet the environmental goals set in international agreements and European strategies such as the SET Plan or the European Green Deal.

> **“ SNETP is playing its role (together with the entire nuclear community) as the association gathering the best experts in Europe in nuclear fission technology able to foster R&D&I collaborative projects and strengthen the position of the European community as leader in this technology that has been proven to provide low carbon, reliable and competitive energy useful for Europe to reach its objective of carbon neutrality by 2050.**

1. INTRODUCTION

The civil nuclear sector has experienced major events during the last two decades, with the tsunami in Japan effecting the Fukushima nuclear plants in 2011 and the financial crisis in 2008-2009 which triggered the evolution of energy policy in European member states and strongly affected investments in nuclear capacities. The sector has to face new challenges and some anti-nuclear groups have been calling for the exclusion of nuclear from the list of sustainable activities under the European Green Deal plan. Most of the arguments being put forward are not based upon scientific evidence. In fact:

Nuclear currently provides more than 47 % of the low-carbon electricity generation in the EU. **Nuclear also saves half a billion tons of CO2 emissions every year in Europe compared to fossil fuels, which is more than the emissions of the UK or France alone;**

Life cycle emissions produced by nuclear compare favourably with those from renewables technologies. According to Intergovernmental Panel on Climate Change (IPCC) figures, nuclear emissions are equal to those of wind power and are four times lower than solar power, with 12g of CO2/KWh. The IPCC analysis for nuclear includes the whole life cycle, including uranium mining, enrichment and fuel fabrication, plant construction, use, decommissioning and long-term waste management;

An analysis of recognised Levelized Cost of Energy (LCOE) figures, clearly shows that nuclear energy is competitive with other low-carbon power sources. Again, based on the IPCC figures, the LCOE of nuclear is on average half of solar or offshore wind and comparable to onshore wind;

Moreover, the Levelized Cost of Electricity does not consider the value of stable, reliable power supply. Nuclear power generation doesn´t rely on weather conditions and provides reliable power to industry, transport, hospitals, homes and businesses 24 hours a day, 365 days a year. The current COVID-19 crisis has provided clear evidence that it is in the time of a crisis when scarcity defines value. **Ensuring reliable power should always remain an imperative during policymaking;**

With a strong, positive regulatory framework in place, there is huge potential to decrease build time and cost of new nuclear projects. Recent projects on modernisation and harmonisation of the nuclear supply chain have shown that streamlined requirements on vendors, combined with the benefits of series build, can rapidly increase the speed of new-builds while decreasing costs and maintaining safety;

Nuclear can be flexible and does not undermine the deployment of renewables. Recent findings by the Massachusetts Institute of Technology (MIT) have shown that operating nuclear plants flexibly can reduce overall electricity costs and cut carbon emissions in electric power systems. Developing and releasing the potential of the Small Modular Reactors (SMRs) can also contribute to making nuclear reactors more scalable and potentially decreasing costs and build time requirements;

1

Flexible nuclear operation can help add more wind and solar to the grid. Nuclear and renewables should be partners in fighting climate change, but sadly, some anti-nuclear activists are building barriers and support the narrative of nuclear power undermining the deployment of renewables. The time for action to fight climate change is very tight. Thus, all low-carbon and clean technologies that can contribute to the fight against climate change must be allowed to contribute and be part of the solution;

Both IAEA and EU regulatory framework ensure that nuclear power plants comply with the highest safety standards. The framework applies to the full nuclear lifecycle including the management of nuclear waste and ensures that nuclear waste is safely managed in the long-term. Interim storage solutions that are fully operational worldwide are licensed by competent authorities, comply with the highest safety regimes, are developed in a transparent manner and undergo strict environmental impact assessments;

Nuclear power plants are protected against rising sea levels and flooding. The International Atomic Energy Agency (IAEA) global safety standards require operators to take account of risks arising from rising sea levels. It is also important that even in the worst-case scenarios modelled by the IPCC if sea levels rise one meter by 2100, the current nuclear fleet will be already decommissioned, and the new-build power plants can easily be adapted to any potential challenges when being designed and built;

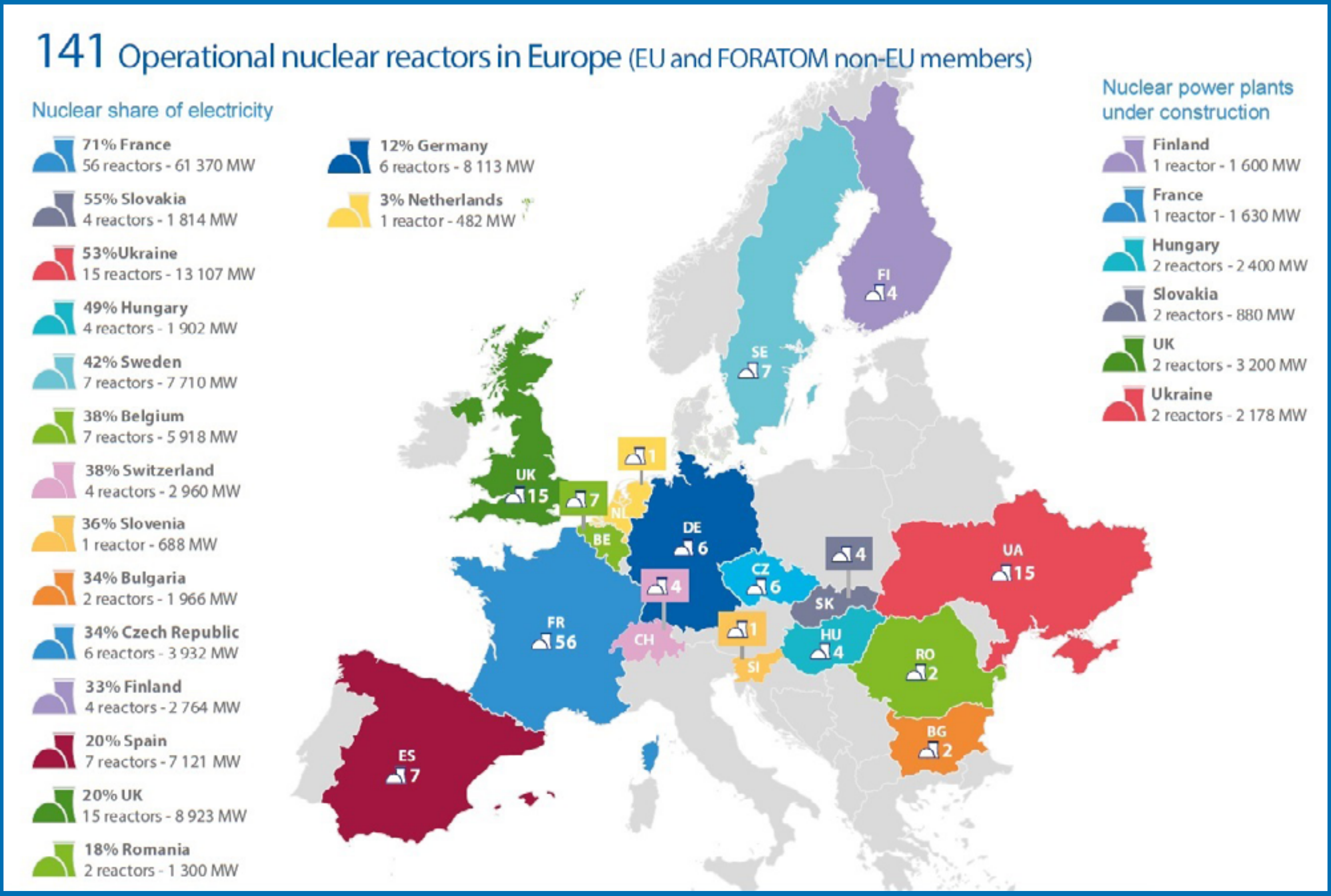
At the same time **the nuclear industry, in cooperation with regulators, have identified and, in some cases, have already started to deliver facilities for the safe, long-term disposal of nuclear waste.** The European Commission has recently acknowledged that Finland, France and Sweden are advancing their solutions for long term storage of high-level waste.

Nuclear power is an important and established power source for European citizens and industries and is crucial for the stability of energy systems. The existing strict regulatory regime defines the “Do No Significant Harm” principle for the nuclear sector and guarantees that nuclear power plants are operated in a safe and sustainable manner, including their decommissioning and spent fuel management.

International bodies including the Intergovernmental Panel on Climate Change and the International Energy Agency acknowledge the role of nuclear in the fight against climate change and their analysis and conclusions provide compelling evidence that nuclear power is safe, competitive and sustainable. Also, the European Commission itself has recognized that nuclear power, together with renewables, should be the backbone of the climate-neutral energy system.

By 2020, nuclear reactors provide about 26% of electricity generation in Europe, operating a total of 141 nuclear power plants. There are 10 plants under construction, and more are planned. Notably, nuclear energy is a reliable source of energy, producing electricity at full power for nearly 90% of the time, thus enhancing the security of supply at prices which are among the lowest compared to other sources of energy. The nuclear energy industry supports around 800 000 jobs in Europe (all figures and the map below derived from Foratom, 2019), and substantial exports to non-EU countries.

800 000 jobs in Europe are supported by **nuclear energy**



© FORATOM (Source: Eurostat 2020)

1.1 A Mature Sectoral Organization for Research and Innovation

SNETP is a European technology platform, founded in 2007 as a stakeholder forum recognised by the European commission to act as a key actor in driving innovation, knowledge transfer and European competitiveness. Its main role is to develop research and innovation agendas and roadmaps for action at EU and national level to be supported by both private and public funding. It mobilises various stakeholders to deliver on agreed priorities and share information across the EU. SNETPs is focused on nuclear fission technologies, but it also fosters networking opportunities and international cooperation in order to address cross-sectorial challenges.

In fact, over the years, SNETP has succeeded in promoting collaboration between European partners from industry, research, regulators, technical support organisations, and academia. Under its umbrella more than 100 collaborative projects have been initiated, monitored, and carried out by its pillars, in addition to many collaborative agreements that have been launched with various European and international organisations. With this, the role of nuclear fission in providing safe, reliable, and affordable electricity, with low greenhouse gas emissions, has been reinforced to contribute positively against climate change as part of the European Green Deal. Such collaboration between the European experts and at the international level allows assessing the maturity of the existing technologies and the creation of innovative ones. First of all, to continuously seek to improve safety, performance and efficiency of the existing nuclear installations being industrial or dedicated for R&D and training. Secondly, to develop and prepare the next nuclear generation aiming at closing the fuel cycle and permitting the use of nuclear for other applications such as desalination, process heat, and hydrogen production.

> ***SNETP has succeeded in promoting collaboration between European partners from industry, research, regulators, technical support organisations, and academia.***

Since its foundation, the platform has promoted collaboration between European partners from industry, research entities, safety organizations and academia with the vision to:

> **‘aim at achieving a sustainable production of nuclear energy, a significant progress in economic performance, and a continuous improvement of safety levels as well as resistance to proliferation through the development and deployment of potentially sustainable nuclear technologies, as well as actions to harmonise Europe’s training and education, whilst renewing its research infrastructures’ (SNETP, 2007).**

SNETP has a mature structure reflecting these three strategic themes in its three pillars: NUGENIA, ESNII and NC2I which have well-established programs and governance (thanks to dedicated EC funded projects) for succeeding in their missions:

NUGENIA
Nuclear Generation II&III Alliance

Conduct a research and development programme of nuclear fission technologies, with a focus on Generation II & III nuclear plants, through providing a scientific and technical basis to the community by initiating and supporting international R&D collaborative projects and programmes with added value to the end-users.

ESNII European Sustainable Nuclear Industrial Initiative

Demonstrate Generation IV Fast Neutron Reactor technologies, together with supporting research infrastructures, fuel facilities and R&D work.

NC2I Nuclear Cogeneration Industrial Initiative

Demonstrate an innovative and competitive energy solution for the low-carbon cogeneration of heat and electricity based on nuclear energy.

The members of SNETP and its pillars decided in 2017 to pursue an evolution of the platform towards a legal association to provide:

- The capacity for establishing “win-win” agreements with international agencies and other legal entities for extending SNETP network;
- Increasing SNETP visibility and pertinence as the European association leading the fission R&D programme, in its relationship with stakeholders and the European Commission;
- Ensuring the financial means to provide services to its members while ensuring a technical secretariat, this way increasing the attractiveness of the platform.

Final approval of all members on 22 May 2019 and a royal decree by the King of Belgium on 2 September 2019 completed this transition. The aim of the legal association is to strengthen the positioning of nuclear energy in today’s and tomorrow’s European energy mix and consolidate European research, development, demonstration and innovation on fission technologies.

1.2 Added Value

The SNETP R&D&I priorities are based on the core program of its three pillars: NUGENIA, ESNII, and NC2I. The added value of the platform lays in the global vision it aims to develop in support of nuclear systems, the identification of major milestones for ensuring R&D fission alignment with the nuclear energy challenges, and also, the evaluation of cross cutting issues which could open new routes for collaboration among the pillars and address cross-sectorial challenges while optimising the resources and infrastructures. The reference documents of SNETP, are published on a regular basis and circulated through the European and international community for highlighting these high-level objectives and challenges, and monitoring the progress.

Strategic Research and Innovation Agenda

Deployment Strategy

In its last version, the Deployment Strategy 2015 displayed an integrated vision of the SNETP activities spanning Generations III and IV and Co-generation development till 2050, in connection with the operations and foreseen evolution of the European nuclear fleet. Cross cutting issues were identified in basic technology, and a strong interaction in development and application of methods, tools, and transfer of knowledge was promoted. A new forum, in line and joined with the existing NUGENIA Forum, is being initiated to enhance the joint programming among the three pillars, in a view to facilitate the achievement of their own core program.

Regarding the collaboration outside SNETP, working groups have been activated:

- For sharing information on spent-fuel and nuclear waste with the ‘Implementing Geological Disposal of radioactive waste Technology Platform’ (IGDTP), as the reference technology platform on geological disposal;
- On nuclear material research with the European Energy Research Alliance Joint Programme on Nuclear Materials (EERA/JPNM).

New services may be developed by SNETP members, and this will be facilitated by its evolution towards a legal association.

SNETP represents and supports a European wide collaboration and view. To this aspect, a near future challenge will be to maintain the collaborations between the EU and UK partners. The UK has indicated (NIRAB, 2019) that it is important to ensure that the mechanisms are in place to ensure the impact on collaboration with Europe is minimised.

1.3 Structure of the Strategic Research and Innovation Agenda

This SRIA intends to provide a holistic SNETP view on the current agenda for strategic research and innovation identifying:

- ✓ common challenges;
- ✓ specific challenges;
- ✓ cross cutting challenges.

The next chapter will highlight the future of nuclear energy in Europe by considering international energy outlooks and their impact on nuclear energy in Europe, by summarising the benefits and potential of nuclear energy, and by summarising the SNETP Deployment Strategy established a couple of years ago. After that, the third chapter will present the common and specific challenges with respect to reactor technology discussing challenges in operation and construction, in-service inspection, qualification and non-destructive examination, advanced reactor development and the next generation of fission reactors, and development of small modular and mini reactors. Chapter four will deal with enabling conditions such as safety of nuclear power plants, development of fuel, the fuel cycle, and spent-fuel management, dismantling and decommissioning, and finally social, environmental and economic aspects. The fifth chapter will discuss cross-cutting technologies, like digitalisation, modelling and simulation, and materials. And finally, chapter six will present non-technological cross-cutting aspects like research infrastructure, harmonisation and education, training and knowledge management.

This way, the SNETP Strategic Research and Innovation Agenda 2020 provides an integrated program for the entire SNETP association, which will provide the technical innovations required to meet the strategic vision for nuclear's contribution to a vibrant, low carbon European society.

2. THE FUTURE OF NUCLEAR ENERGY IN EUROPE

2.1 Latest Outlooks

The world today faces a tremendous challenge in providing mankind with the energy it requires. Both the world population and welfare standards continue to rise driving an increasing need for energy, which is outstripping the gains made by increased energy efficiency. Meanwhile, authoritative international studies, e.g. IPCC (2018), warn mankind that we are facing a global warming that threatens our current way of life, due in large part by the means of satisfying this need for energy. There is a sufficient breadth of evidence of the impact of current energy consumption that it is prudent to make substantial efforts to minimise the greater potential impacts predicted for the future.

In summary:

> Mankind faces the issue of possible climate changes due to the increasing CO2 concentrations in our earth atmosphere while at the same time our energy consumption world-wide will rise significantly.

2

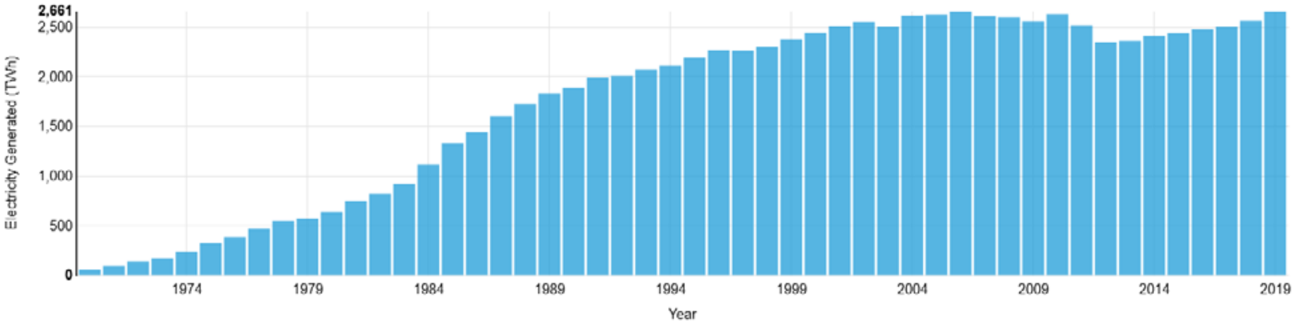
Recent international studies from EC (2016), IEA (2018), IPCC (2018), MIT (2018), IAEA (2018), EC (2017), BP (2019), and OECD/NEA (2019) demonstrate that nuclear energy provides a significant proportion of current low carbon energy and that it has a crucial role in future low-carbon economy and society. In many studies the share of nuclear in the energy mix decreases. However, this is more than compensated by the anticipated increase in overall energy demand, leading to increased need for nuclear energy generation.

There were approximately 440 nuclear reactors operating in 2020. In addition, more than 50 nuclear power reactors are under construction. Nuclear energy provides about 10% of world's electricity production, compared to about 24% by hydro and other renewable sources, and 65% by fossil sources like oil, gas and coal. In advanced economies, nuclear power is the largest low-carbon source of electricity. However, its share of global electricity supply has been declining in recent years. That has been driven by economies where nuclear fleets are ageing, additions of new capacity have dwindled to a trickle, and some plants built in the 1970s and 1980s have been retired. This has slowed the transition towards a clean electricity system. Despite the impressive growth of solar and wind power, the overall share of clean energy sources in total electricity supply in 2018, at 36%, was the same as it was 20 years earlier because of the decline in nuclear. Halting that slide will be vital to stepping up the pace of the decarbonisation of electricity supply.

440 **nuclear reactors operating in 2020**

+50 **nuclear power reactors under construction**

nuclear energy provides about **10%** **world's electricity production**



Global annual nuclear electricity generation
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In Europe, the situation is slightly different with nuclear making up for about 26% of electricity production (about 13% of the primary energy production), compared to 33% renewables and 41% fossil sources (Foratom, 2020). Given the overriding need to reduce atmospheric CO2 urgently, it is clear that nuclear's contribution to low-carbon energy generation is vital in the foreseeable future and that both renewable and nuclear generation are likely to be important. In fact, EC (2016) expects that nuclear energy production will remain stable through increased investments in long term operation and introduction of new nuclear capacity. The fact that the contribution of renewables in the primary energy production will rise to 30% within 2030, which is a rather rapid change in the energy landscape in Europe, implies important challenges to the nuclear sector. The long-term strategy (EC, 2018) states that the share of nuclear in 2050 is still 15%, demonstrating the need for long-term operation (LTO) and new build.

Global energy is increasingly based around electricity. That means the key to making energy systems clean is to turn the electricity sector from the largest producer of CO2 emissions into a low-carbon source that reduces fossil fuel emissions in areas like transport, heating and industry. While renewables are expected to continue to lead, nuclear power can also play an important part along with fossil fuels using carbon capture, utilisation and storage. Countries envisaging a future role for nuclear account for the bulk of global energy demand and CO2 emissions. But to achieve a trajectory consistent with sustainability targets – including international climate goals, the expansion of clean electricity would need to be three times faster than at present. It would require 85% of global electricity to come from clean sources by 2040, compared with just 36% today. Along with massive investments in efficiency and renewables, the trajectory would need an 80% increase in global nuclear power production by 2040.

> *It is clear that nuclear's contribution to low-carbon energy generation is vital in the foreseeable future and that both renewable and nuclear generation are likely to be important.*

The OECD/NEA (2019) analysis of the overall system costs of various energy generation technologies including balancing and grid costs identified that the lowest investments costs to achieve a low-carbon energy mix were associated with scenarios with substantial shares of nuclear. When carbon emissions are reduced with renewables only, the price of electricity rises dramatically. When a combination of nuclear and renewables is used, the price increase is manageable. Nevertheless, there are significant obstacles to new nuclear build in many countries, often associated with public perceptions and financing costs for new reactor construction.

Furthermore, nuclear plants help to keep power grids stable. To a certain extent, they can adjust their operations to follow demand and supply shifts. As the share of variable renewables like wind and solar photovoltaics rises, the need for such services will increase. Nuclear plants can help to limit the impacts from seasonal fluctuations in output from renewables and bolster energy security by reducing dependence on imported fuels.

Realising the need for nuclear growth, the MIT (2018) study provided suggestions to overcome the high cost of nuclear plant construction, one of the biggest hurdles. These include modularisation in construction, improved plant (rather than just reactor) design and international alignment of regulatory requirements. All of which are addressed within this SRIA.

Individual countries are entitled to make their own decision on the sources of energy that they wish to use. As a technical organisation, SNETP's contribution is to provide reliable and accurate information of the benefits, costs and detriments associated with the use, or not, of nuclear power and to articulate these within the European society and its policy-making structures. To that end, relevant activities to that end are contained within this SRIA.

2.2 Benefits and Potential of Nuclear Energy

Nuclear energy is an important contributor to all three main pillars of EU energy policy set out in the SET-plan (EC, 2017): environmental sustainability, security of supply and economic competitiveness. Nuclear provides 26% of the EU's electricity and about half of the EU's low-carbon electricity. Nuclear has one of the lowest life-cycle climate impacts of any energy source. According to the IPCC (2018), greenhouse gas emissions from the nuclear cycle average around 12gCO2equivalent/kWh, which is similar to wind power and only one quarter of the emissions of solar photovoltaics, for example.

Environmental sustainability

When compared with other sectors, the nuclear industry generates a very limited amount of waste. The average EU citizen generates about 1.4 tonnes of waste per year, of which 54kg are toxic waste and only 54g are classed as radioactive. Unlike other sectors, the nuclear industry segregates and manages its waste safely, with dedicated funding set aside for its ultimate disposal. Because nuclear is energy-intensive, the area of land occupied by a nuclear power plant is, for example, less than one-hundredth of the area required for a wind farm of equivalent electrical output. Nuclear reactors provide both heat and electricity. Waste heat can be used for district heating, desalination or to power industrial processes. High temperature reactors hold the promise of being able to link directly with energy-intensive cement making or metallurgical plants, or to produce hydrogen from water without the need of fossil fuels. Direct linkage provides benefits by eliminating otherwise unavoidable losses associated with energy conversion or carbon emission from conventional high temperature heat sources.

A major European Union-funded research study known as ExternE, or Externalities of Energy, undertaken over the period of 1995 to 2005 found that the environmental and health costs of nuclear power, per unit of energy delivered, was €0.0019/kWh. This is lower than that of many renewable sources including the environmental impact caused by biomass use and the manufacture of photovoltaic solar panels, and was over thirty times lower than coals impact of €0.06/kWh, or 6 cents/kWh.

Security and flexibility of supply

In terms of security of supply, nuclear is beneficial to the European electricity grid because it has high availability, can operate flexibly and helps with frequency stabilisation. With their reliable supply of low-carbon electricity, nuclear power plants are increasingly important in today's power systems marked by the growing share of variable, distributed renewable energy. Unlike other technologies, they **generate energy from a very small amount of fuel.** New fuel only has to be added only every 12 or even 24 months (depending on the characteristics of the plant and operational and fuel cycle plans). New fuel for nuclear power plants can easily be stored for up to several years.

Uranium can be sourced from a variety of politically stable countries around the world, meaning that fuel imports are not subject to potential disruption. Identified exploitable resources of uranium will last for well over 300 years on current projections using slow-neutron, light water reactors. Next-generation fast-neutron reactors could increase this to thousands of years, when fully deployed.

Nuclear power plants generally supply baseload power. This is mainly:

- ✓ to maximise output: nuclear power has a very low electricity production cost;
- ✓ to maximise security of supply: nuclear power plants are a very reliable generation source;
- ✓ possible if the power system requires no supply-side response from nuclear to daily fluctuations (i.e. to meet peak load demand).

As the share of variable renewable energy in the generation mix grows, giving rise to advanced grid solutions, nuclear power plants are increasingly faced with the flexible operation challenge.

In some power systems, nuclear power plants are expected to provide additional ancillary services such as frequency control by adjusting their output to respond to variations in demand.

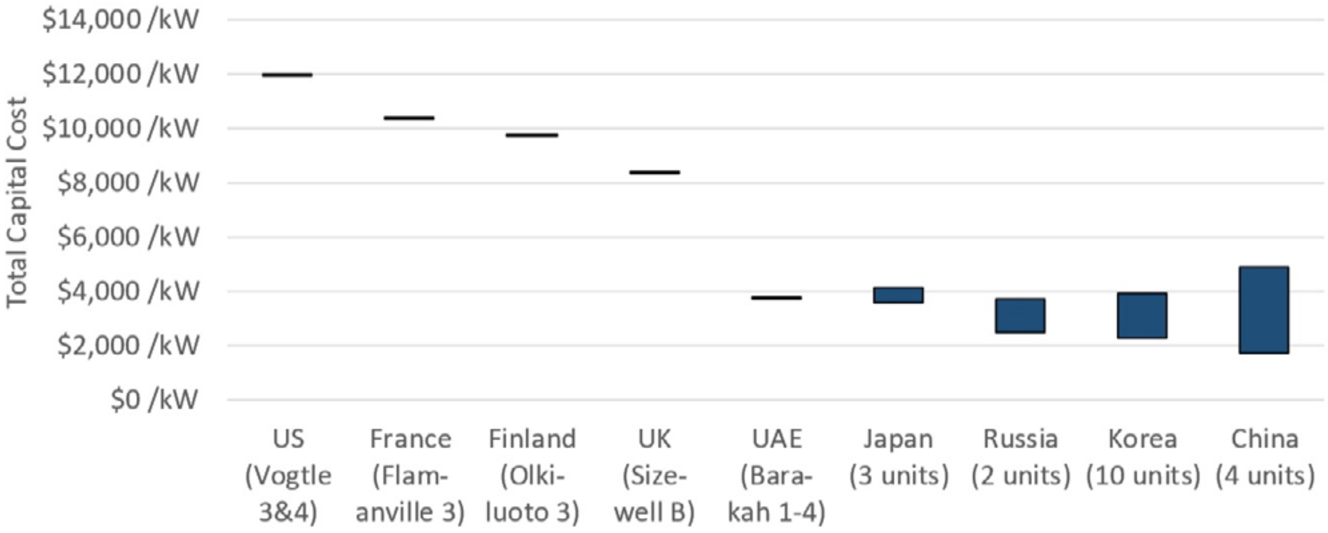
In France and Germany, for example, most nuclear power plants contribute substantially to the provision of ancillary services by operating flexibly and meeting peak load demand. The existing 2nd generation nuclear reactors are technically capable of implementing flexible operation modes.

Meanwhile, the design of **3rd generation nuclear reactors** is even better suited to flexible load following and frequency control, **allowing for very quick changes in output** with ramp rates of 5% of full power per minute. For a 1000 MW power plant, this means as much as 50 MW per minute.

This development makes nuclear power one of the sources that **can deliver a relatively quick response in providing ancillary services.**

Economic competitiveness

IEA (2015) comparisons of levelized costs of electricity (LCOE) for new-build production facilities in 2020 for a range of sources at 10% discount rate show that nuclear and onshore wind are the two most competitive low-carbon generation technologies, with similar median electricity prices. However, long-term operation of existing nuclear power plants, when the capital cost has been depreciated, will produce considerably cheaper electricity than new build – even three times cheaper according to IEA. Nuclear is therefore an economically competitive source of low-carbon electricity. In the future, as the share of intermittent renewable electricity grows and nuclear will be required to operate more flexibly, the costs of curtailment, back-up and system balancing for renewables will become more significant. It is likely that different market models based less on marginal costs and more on capacity will need to be introduced. Nuclear will remain competitive in this situation, especially in markets where full system costs and externalities are taken into account.



© ETI Nuclear Cost Drivers Project (2018)

The sector also provides other benefits. In a report published by Deloitte (2019), it was noted that the nuclear sector employs more than 1.1 million people, generating a gross domestic product of the order of 0.5 trillion euro per year.

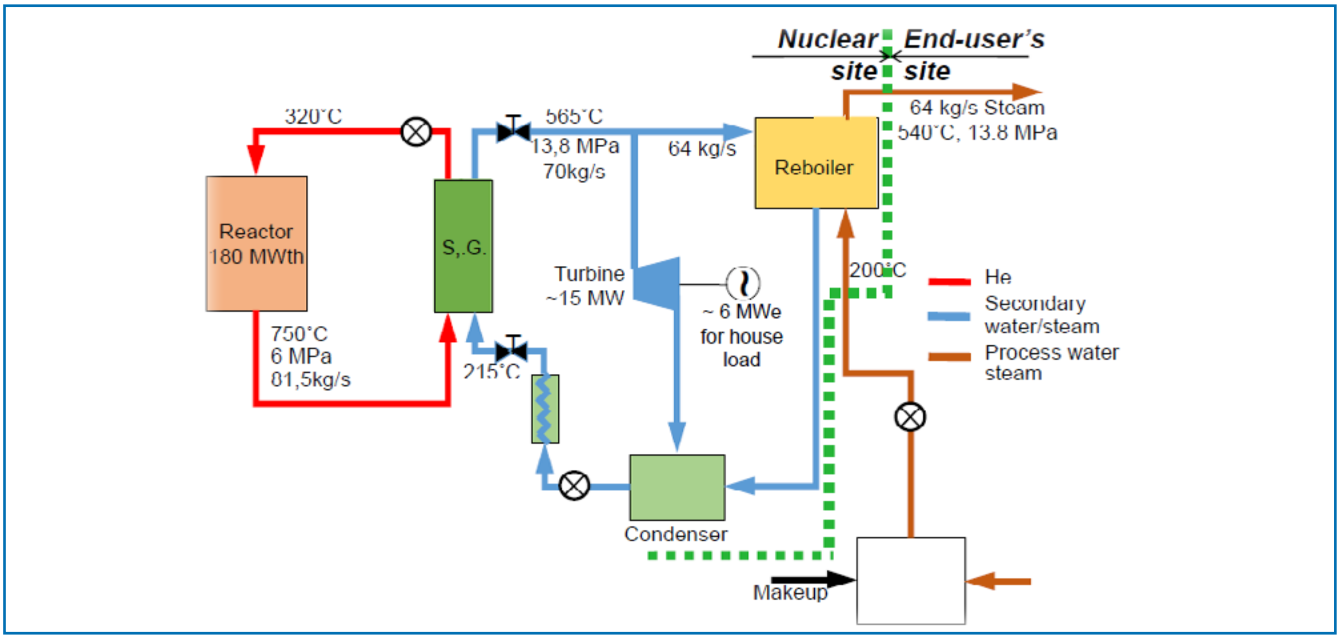
OECD (2018) concludes that direct employment during site preparation and construction of a single unit 1000 MW advanced light-water reactor is approximately 1200 professional and construction staff, or about 12000 labour years in total; during a conservative 50 years of operation, approximately 600 administrative, operation and maintenance, and permanently contracted staff are employed annually, or about 30000 labour years; for up to 10 years of decommissioning, about 500 people are employed annually, or around 5000 labour years; over an approximate period of 40 years, close to 80 employees are managing nuclear waste, totalling around 3000 labour years. When indirect and induced employment is added, the total employment in the nuclear power sector of a given national economy is therefore roughly 200000 labour years over the life cycle of one gigawatt of nuclear generating capacity.

Looking ahead towards 2050, an article published in SETIS (2014) foresaw that approximately 100 of the EU's nuclear plants would have their operational lives extended for between 10 and 20 years and that 100 new NPPs would be built. The associated engineering and construction works would entail investments of around €90 and 500 billion respectively. The EC (2017) PINC communication puts the expected LTO investment figure at €40-50 billion and the new build investment at €350-450 billion. Whichever set of figures you take, the resulting investment in jobs and the local economy is very significant. On top of that, jobs in nuclear generally require higher levels of qualifications, training and skills than comparable jobs in other energy sectors, meaning that the contribution to the EU's growth and prosperity is correspondingly higher.

> ***The nuclear sector employs more than 1.1 million people, generating a gross domestic product of the order of 0.5 trillion euro per year.***

Non-electric application of nuclear energy

It should be noted that electricity represents only approximately 20% of the energy consumed in Europe. The remainder of the energy production is essentially heat for industry and district heating as well as energy for transport. Currently, that energy production is almost entirely based on fossil fuel combustion with the concomitant emissions of CO2 and other noxious pollutants. The development of non-electric applications of nuclear energy is therefore a top priority. In fact, non-electric energy applications can be a radical game changer leading to expansion of nuclear energy use in Europe. Non-electric applications powered by nuclear energy could present sustainable solutions for a number of energy challenges that current and future generations will have to face. There is growing interest around the world in using nuclear energy for such applications as seawater desalination, hydrogen production, district heating and various industrial applications.



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Nuclear cogeneration is the integration of nuclear power plants with other systems and applications. The heat generated by the nuclear power plants can be used to produce a vast range of products such as cooling, heating, process heat, desalination and hydrogen. The use of nuclear energy for cogeneration provides many economic, environmental and efficiency-related benefits. Cogeneration options may be different; depending on the technology, reactor type, fuel type and temperature level.

The use of nuclear energy for cogeneration also provides the benefit of using nuclear fuel in more efficient and eco-friendly manner. Energy and exergy analyses show that the performance of a nuclear power plant may be increased if it is used in a cogeneration mode. The use of nuclear energy for cogeneration applications can also lead to a drastic reduction in the environmental impact. However, integrating a nuclear power plant with any other sub-system for cogeneration can greatly be affected by the performance parameters of the nuclear power plant and the site where it is located.

There are major types of nuclear power reactors such as: water cooled reactors, liquid metal cooled reactors, high temperature gas cooled reactors, and molten salt reactors. Water cooled reactors are suitable for use in district heating and desalination systems due to their working temperature range of 280-325°C. The working temperature range of other types including liquid metal cooled and molten salt reactors are from 500-800°C makes them suitable for various cogeneration options. The high working temperature range of 750-1000°C of high temperature gas cooled reactors using helium as a coolant makes them suitable for generation of process heat, desalination of sea water and hydrogen in cogeneration mode.

> ***The heat generated by the nuclear power plants can be used to produce a vast range of products such as cooling, heating, process heat, desalination and hydrogen.***

Other potential area of process heat applications of nuclear power which of interest to Member States and supported by the Agency is the oil sand/oil shale extraction and enhancement of oil recovery (such industrial applications have been applied in Canada, Switzerland and India).

Other benefits of nuclear energy

Nuclear energy protects air quality by producing massive amounts of carbon-free electricity. It powers communities in 14 EU member states and contributes to many non-electric applications, ranging from the medical field to space exploration, as well as agriculture.

Nuclear energy reliably providing more than one quarter of the EU's electricity without emissions of noxious gases and with very low life-cycle discharges of greenhouse gases. Kharecha and Hansen (2013) estimate that, since the 1970s, nuclear power has prevented nearly three-quarters of a million deaths in OECD Europe that would have otherwise been caused by air pollution from fossil fuels.

> ***Since the 1970s, nuclear power has prevented nearly three-quarters of a million deaths in OECD Europe that would have otherwise been caused by air pollution from fossil fuels.***

The radioisotopes produced in Europe's reactors have widespread use in medicine, industry, agriculture and research in all Member States. More than 500 million diagnostic procedures using x-rays or radioisotopes are carried out in Europe each year, and more than 700000 European healthcare workers use nuclear and radiation technology on a daily basis. Furthermore, nuclear medical imaging, which combines the safe administration of radioisotopes with camera imaging, helps physicians locate tumours, size anomalies, or other problems. Criminal investigators frequently rely on radioisotopes to obtain physical evidence linking a suspect to a specific crime. They can be used to identify trace chemicals in materials such as paint, glass, tape, gunpowder, lead, and poisons.

A great deal of what is known about deep space has been made possible by radioisotope power systems. These small nuclear power sources are used to power spaceships in the extreme environments beyond terrestrial atmosphere. Radioisotope power systems are proven to be safe, reliable, and maintenance-free for decades of space exploration, including missions to study Jupiter, Saturn, Mars, and Pluto.

Finally, farmers can use radioisotopes to control insects that destroy crops as an alternative to chemical pesticides. In this procedure, male insect pests are rendered infertile. Pest populations are then drastically reduced and, in some cases, eliminated. Nuclear energy is also harnessed to preserve our food. When food is irradiated, harmful organisms are destroyed without cooking or altering the nutritional properties of the food. It also makes chemical additives and refrigeration unnecessary, and requires less energy than other food preservation methods.

2.3 European Deployment Strategy

The purpose of the Deployment Strategy in 2015 (DS 2015) was to define the programme for delivery of SNETP's global vision and alignment with the challenges and planning assumptions for nuclear energy. This is achieved by providing:

- R&D programs up to 2050 that deliver progress towards the SNETP vision, consistent with the European energy context and policy;
- Clearly defined technical objectives within the R&D programs for each nuclear system to which R&D projects of high technical value can be aligned;
- Transversality, through identification of cross cutting issues, not only within SNETP but also with other European technology platforms;
- The basis for defining funding resources required to deliver the vision, with an equitable share between public and private contributions.

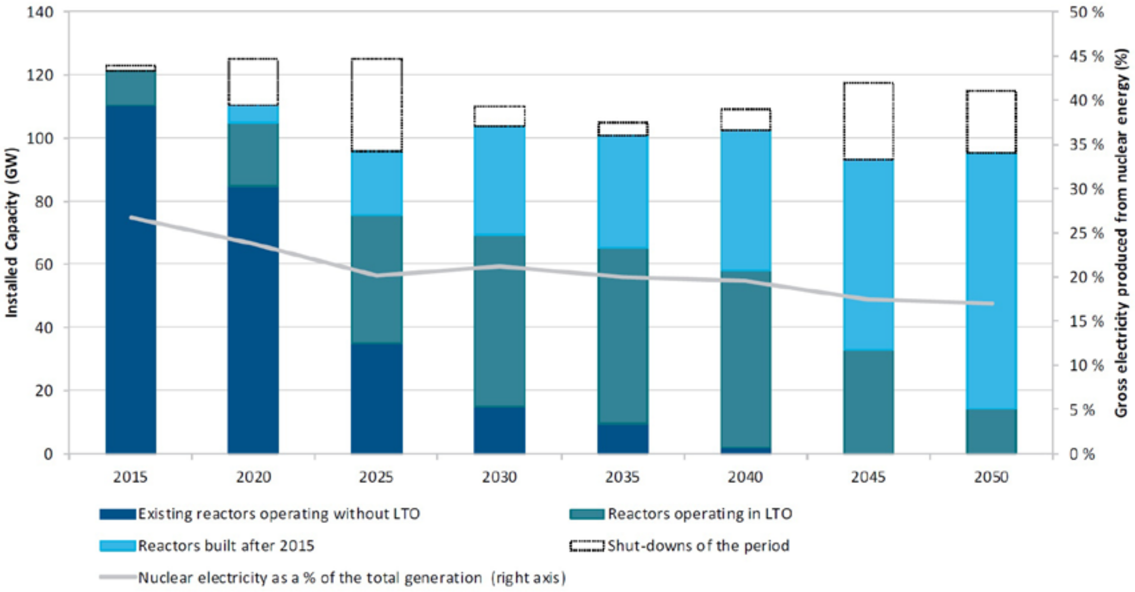
The Deployment Strategy is periodically reviewed to ensure that it represents the optimum path to meeting the SNETP vision for delivering societal benefits from nuclear technologies and provide relevant prioritisation to guide delivery of EC framework programmes.

2.3.1 Challenges and planning assumptions for nuclear energy

Nuclear system technology drivers: safety & performance

Nuclear energy generation is a mature and reliable technology, operating under established legislative codes and scrutinized by independent safety authorities. Electricity is supplied at stable and competitive prices, generating low greenhouse gas emission, and with established and secure supply chains for fuel, maintenance operations and new build. For maintaining a leading role in electricity production, nuclear energy systems need to comply with both a safety and performance vision and to continually improve in the delivery of both of these. Examples include:

- Safety review and monitoring, including the consequences of the future energy mix with increased share of renewables and the consequences on the flexibility of the network;
- Improving economics for initial investment, operating cost, back end costs;
- Increased sustainability: optimisation of resources use and minimisation of nuclear waste;
- Minimization of environmental impact: minimizing discharges, waste management, fuel cycle.



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The safe and reliable operation of the European nuclear fleet requires the availability of appropriate supply chain options. The average age of the nuclear fleet in Europe is 35 years[1]. Without the lifetime extension of nuclear power plants in Europe, 90% of current nuclear capacity will be shut down by 2035 and will thus need to be replaced. Nuclear is an important contributor of low-carbon energy which helps the EU mitigate climate change. As stated in the European Commission's "A Clean Planet for All" strategic vision, nuclear, together with renewables, will form the backbone of a carbon-free power sector in 2050 providing an estimated 15% of electricity demand.

Continuous improvement in operational practices and nuclear safety are of fundamental importance to the European nuclear industry. Safety upgrades are an integral part of plant lifetime extension programmes. As a consequence, securing a strong and diversified supply chain is essential to ensuring the high levels of safety, quality and reliability required for new build projects and long-term operation alike.

Technology evolution of reactors

The original design lifetime of the existing nuclear power plants (NPPs) is around 40 years. European utilities, alike others worldwide, are investing in plant lifetime extension beyond the 40-year limit. Besides long term operation, in the countries that have selected nuclear energy for electricity generation and intend to build new ones, Generation II reactors will be replaced by Generation III technology, which implements new and innovative features for improved performance and safety, while extending the design lifetime to 60 years. It is therefore expected that Generation III reactors will be key players for electricity production throughout the 21st century.

The European Commission in 2010 launched the European Sustainable Nuclear Industrial Initiative (ESNII), one of the pillars of SNETP-association, which supports three (out of the 6 concepts supported by the GEN IV international Forum -GIF) Generation IV fast reactor projects as part of the EU's plan to promote low-carbon energy technologies.

Between 2010 and 2018 ESNII has taken forward: the Astrid sodium-cooled fast reactor (SFR) proposed by France, the Allegro gas-cooled fast reactor (GFR) supported by central and eastern Europe, and the ALFRED lead-cooled fast reactor (LFR) technology pilot in Romania, supported by the MYRRHA lead-bismuth facility in Belgium. Evolutions of these technologies and projects in Europe beyond 2019 are dealt with below.

These long-term projects are under preparation, with a clear objective to provide a sustainable nuclear fuel cycle. This will be achieved with fast neutron technology which allows fuel multi recycling and offers capabilities for waste minimization and/or transmutation. Challenges related to safety and economic competitiveness are still key drivers to cope with, as well as increasing resistance against proliferation risk.

The industrial deployment of such fast reactors in Europe is not foreseen before the second half of the 21st century and will likely be progressively introduced at a slow pace in order to take benefit from lessons learnt from prototype and from research reactors operations throughout this century. The availability of dedicated fuel for fast neutron reactors, which requires LWR fuel reprocessing and adequate fuel cycle facilities, is another strong constraint.

Within the GIF program, Sodium-cooled fast reactor development is part of several national programs at different levels of advancement: The French government announced the termination of the ASTRID project in 2019. However, the post ASTRID Sodium R&D program in France in tight connection with Japan is supported. Other Sodium projects are pursued worldwide: the VTR project in the USA, the CFR600 project in China, the PFBR (Prototype Fast Breeder Reactor) in India, and industrialization is proceeding in Russia where the BN800 reactor has reached criticality in 2015 and produced 5,8 TWh on the grid in 2017. The Belgian Government decided in 2010 to select and support the Accelerator Driven System (ADS) project, called MYRRHA, and decided in 2018 to allocate a special endowment of 558 M€ for the realisation of the MYRRHA installation at the SCK•CEN Mol site. The lead cooled fast reactor is considered as a short-term alternative Generation IV technology, with the ALFRED demonstrator selected to be built in Romania and a large R&D program ongoing in Europe in its support, along with the BREST300 reactor development in Russia. The gas cooled fast reactor is the longer-term alternative Generation IV technology, proceeding with the intermediate objective of building the small demonstration reactor ALLEGRO.

The table below indicates the different designs supported by the GIF and the experience available worldwide.

Reactor design	**Operating Experience**
SFR	More than 400 reactor operating years in various countries
LFR	80 reactor operating years (Russian submarines)
HTGR	30 operating years in prototypes and demonstrators in various countries
MSR	4 operating years in an experimental reactor in the USA
GFR	0 operating experience
SCWR	0 operating experience but 400 supercritical coal-fired plants operational

In addition to electricity generation, nuclear systems can offer process heat generation with low-carbon emissions. It is worth recalling that fossil fuel combustion is the main source of heat supply to European energy intensive industries, which represents around 20% of Europe's CO2 emissions. Other process heat applications have been identified: large-scale hydrogen production, district heating, sea water desalination, and coal gasification or liquefaction. Although not widespread, nuclear cogeneration is already a reality. Depending on the targeted temperature range, different reactor technologies are envisioned, among which the High Temperature Gas-cooled Reactor.

Small Modular reactor

Worldwide, there is strong interest in small and simpler units for generating electricity from nuclear power, and for process heat. This interest in small and medium nuclear power reactors is driven both by a desire to reduce the impact of capital costs and to provide power away from large grid systems. The technologies involved are numerous and very diverse. Small modular reactors (SMRs) are defined as nuclear reactors generally 300MWe equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times.

Today, due partly to the high capital cost of large power reactors generating electricity via the steam cycle and partly to the need to service small electricity grids under about 4 GWe, there is a move to develop smaller units. These may be built independently or as modules in a larger complex, with capacity added incrementally as required. Economies of series are envisaged due to the numbers produced. There are also moves to develop independent small units for remote sites. Small units are seen as a much more manageable investment than big ones whose cost often rivals the capitalisation of the utilities concerned. An additional reason for interest in SMRs is that they can more readily slot into brownfield sites in place of decommissioned coal-fired plants, the units of which are seldom very large – more than 90% are under 500 MWe, and some are under 50 MWe.

Four main options are being pursued: light water reactors, fast neutron reactors, high temperature gas cooled reactors and various kinds of molten salt reactors. The first has the lowest technological risk, but the second can be smaller, simpler and with longer operation before refuelling. SMR development is proceeding in Western countries with a lot of private investment, including small companies. The involvement of these new investors indicates a profound shift taking place from government-led and -funded nuclear R&D to that led by the private sector and people with strong entrepreneurial goals, often linked to a social purpose. That purpose is often deployment of affordable clean energy, without carbon dioxide emissions.

Generally, modern small reactors for power generation, and especially SMRs, are expected to have greater simplicity of design, economy of series, production largely in factories, short construction times, and reduced siting costs. Most are also designed for a high level of passive or inherent safety in the event of malfunction. Also many are designed to be emplaced below ground level, giving a high resistance to terrorist threats. Many safety provisions necessary, or at least prudent, in large reactors are not necessary in the small designs forthcoming. This is largely due to their higher surface area to volume (and core heat) ratio compared with large units. It means that a lot of the engineering for safety including heat removal in large reactors is not needed in the small reactors. Since small reactors are envisaged for replacing fossil fuel plants in many situations, the emergency planning zone required is designed to be no more than about 300 m radius. The main features of an SMR, include:

- Small power and compact architecture and usually (at least for nuclear steam supply system and associated safety systems) employment of passive concepts. Therefore there is less reliance on active safety systems and additional pumps, as well as AC power for accident mitigation;
- The compact architecture enables modularity of fabrication (in-factory), which can also facilitate implementation of higher quality standards;
- Lower power leading to reduction of the source term as well as smaller radioactive inventory in a reactor (smaller reactors);
- Potential for sub-grade (underground or underwater) location of the reactor unit providing more protection from natural (e.g. seismic or tsunami according to the location) or man-made (e.g. aircraft impact) hazards;
- The modular design and small size lends itself to having multiple units on the same site;
- Lower requirement for access to cooling water – therefore suitable for remote regions and for specific applications such as mining or desalination;
- Ability to remove reactor module or in-situ decommissioning at the end of the lifetime.

> ***Modern small reactors for power generation, and especially SMRs, are expected to have greater simplicity of design, economy of series, production largely in factories, short construction times, and reduced siting costs.***

Licensing is potentially a challenge for SMRs, as design certification, construction and operation licence costs are not necessarily less than for large reactors. SMR standardization of licensing and harmonisation of regulatory requirements are needed in order to use their full potential, such as:

- Because of their small size and modularity, SMRs could almost be completely built in a controlled factory setting and installed module by module, improving the level of construction quality and efficiency;

- Their small size and passive safety features lend them to countries with smaller grids and less experience of nuclear power;
- Their size, construction efficiency and passive safety systems (requiring less redundancy) can lead to easier financing compared to that for larger plants;
- Moreover, achieving 'economies of series production' for a specific SMR design will reduce costs further.

Fuel Cycle

Whatever the reactor technology, the fuel cycle remains an important consideration. Regarding fuel resources, uranium supply is currently more than adequate to meet demand for the next centuries. New uranium sources are being investigated (sea, phosphate…) and at the same time, new extraction processes are being developed for improved economics. The spent nuclear fuel from the operation of nuclear power plants needs to be managed in a safe, responsible and effective way. Several possibilities exist to deal with the spent fuel, and the strategy adopted by the country depends strongly on its overall energy strategy and its national policy.

- Open fuel cycle: the spent fuel is disposed in geological repository. This option has been selected by Finland and Sweden;
- Closing the fuel cycle: the spent fuel is not considered as a waste, and is recycled following adequate processing. This option has been selected by France;
- Waste management: the quantity, level of radioactivity and lifetime will depend on the fuel cycle strategy i.e. open, partially or fully closed fuel cycle;
- Transmutation option for high level waste: Minor actinides could be burned in fast neutrons reactors, reducing by that way the volume of high-level ultimate wastes to be stored;
- Sustainability: fuel recycling offers a step towards sustainability, depending on the number of recycling operations. In principle, multi-recycling in fast neutron reactor would result in a self-sustaining cycle.

Cross cutting issues:

Once the Generation IV reactors technologies considered in ESNII are available and mature, the transition from current LWR technology to fast neutron reactors will strongly depend on fuel cycle capability and capacity. Initialization of fast neutron reactor deployment relies on the plutonium produced in LWRs and requires reprocessing and recycling facilities to make this plutonium available for fast neutron reactor fuel fabrication. It turns out that the transition from current reactor technology to the next reactor technology requires a similar transition for the fuel cycle facilities, from LWR to fast neutron reactor reprocessing, and with required plutonium throughput increasing step by step, as new fast neutron reactors are started and their fuels are being reprocessed.

The pace and extent of this transition to fast neutron reactors may vary greatly depending on the global energy and political situation. A regional approach scenario, as well as prospective studies could shed light on possible transitions and identify the key industrial risks and success factors. Such studies could start with Russia since it is the most advanced country for fast neutron reactor and closed fuel cycle technologies.

From the technological view point, the nuclear sector shall continue its learning curve by adapting new technologies (e.g. artificial intelligence, big data, data analytics, advanced simulation), new materials, and new fabrication routes to the safety requirements and reinforcement of the supply chain across Europe thanks to agile standardisation of tools and harmonisation of practices.

Decommissioning and dismantling

Given the ageing of the European nuclear fleet (around 27 years on average today) and given the phase out decision in several European countries, such as Germany, Belgium and Switzerland, decommissioning and subsequent dismantling, followed by site declassification or new construction will bring forward many nuclear projects and activities. New characterisation, cleaning and cutting technologies are being developed, as well as new waste forms commensurate with the level of activity, the chemical or physical nature of the waste, and the local or national regulations. Technologies such as digitalisation, simulation, augmented reality or advanced robotics will mature and offer new opportunities.

Energy mix

In a wide range of scenarios mentioned earlier, nuclear energy is currently recognized as the least-cost option for base-load centralised generation, but the cost of renewables is decreasing, leading to a new and complex situation for the network. Given the increased deployment of renewable energy sources, which are intermittent, stability of the overall electricity system will increasingly require new load-following modes for the nuclear capacity. In fact, the transmission system operators, gathered under the ENTSOE, have built new rules for the connection of electricity producers to the grid. These rules, called Gridcodes, may lead to more severe stresses under steady state conditions, and to stability issues. This will be a real challenge for nuclear power plants. New technical requirements for both installed capacity and new build will arise and open routes to innovative technology development.

The proper integration of nuclear energy in the energy mix requires open dialogue with the renewables sector, in such a way that, beyond computer-generated scenarios, a consensual view is reached about the role, realistic possibilities and actual contribution of each technology in connection with the goal of reaching climate neutrality in Europe by 2050.

2.3.2 Strategic vision for R&D program deployment

SNETP's structure has been endorsed to provide a collaborative R&D framework for its members covering three main pillars for nuclear energy system development: light water reactors, fast neutron reactors and co-generation of heat and electricity. For each system, progress has been made in refining the technical objectives and challenges for supporting nuclear product development and for defining R&D topics in depth.

NUGENIA

NUGENIA features an integrated framework for Gen II-III light water reactor technology development, with the general objective of securing the safe and efficient operations of nuclear power plants while increasing their competitiveness and reinforcing the role of nuclear energy as a reliable contributor in the decarbonized energy mix. The overall programme is described in the NUGENIA Roadmap document and the portfolio of R&D projects is managed by experts achieving excellence in nuclear fission research.

NUGENIA
Nuclear Generation II&III Alliance

The NUGENIA research programme has been organized in eight technical areas (TA) with their own fields of expertise:

1. Plant safety and risk assessment
2. Severe accidents
3. Improved nuclear power plant operation
4. Integrity assessment of systems, structures and components
5. Waste management and decommissioning
6. Innovative LWR design and technology
7. Fuel elements
8. European network for inspection and qualification

The installed base as well as newly built reactors are considered within the European fleet, the majority utilising LWR technology. As a complementary approach, eight high level objectives have been identified for reinforcing the synergies between TA specific challenges while giving a clear visibility of Generation II-III system challenges:

- Improve safety in operation and by design
- High reliability, competitiveness of LWR, and optimized functionality of systems
- High reliability of components
- Improve modelling of phenomena in NPPs
- Increase public awareness
- Efficient integration of NPPs into the energy mix
- Prepare the future to avoid technology obsolescence
- Performance and ageing of NPPs for long-term operation

NUGENIA program prioritization

The NUGENIA research program is planned for the next 20 years. Prioritization of the program was achieved with different and complementary approaches:

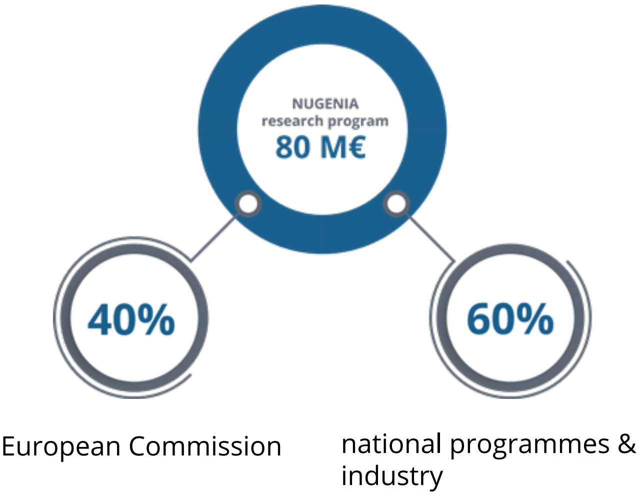
- ✓ Prioritization of technical objectives for meeting the requirements of the high-level objectives;
- ✓ Evaluation of R&D topics according to Technical Area challenges and processes, to national and individual needs, and outcome of finished collaborative projects.

Technical objectives, specific challenges and major milestones to be reached within the next 20 years have been listed in the NUGENIA roadmap available through the website, with a view to highlighting the main orientations of NUGENIA program. This covers basic technology and methods for structural components, fuel, operations (normal – ab-normal and accidental) and systems, to be developed along with the aim of improved safety, performance, harmonization and innovation.

Emphasis is given to mid-term technical challenges since they mainly apply to current LWR design and operations. They should be revised and extended for the next generation of new build, or in case of new regulatory demands, harmonization or up-scaling innovative technology development to on-site application.

Funding resources: public/private

The current collaborative R&D project portfolio in the scope of the NUGENIA research program is equivalent to nearly 80 M€ with a share of 40% coming from the European Commission and 60% from national programs and industry. The projects are carried out by industry, research organizations or technical safety organizations through their own programs, national programs or European calls for proposals.



The overall cost of R&D in support of Generation II- III, is difficult to evaluate. As a rough order of magnitude, the overall cost for the 2015 – 2030 period would range from €5 to 10 billion, mostly supported by Industry. Additional funding should be sought, especially for research infrastructure, including maintenance of existing large testing facilities and/or the construction of new.

ESNII

Concerning fast reactor technologies, four projects have been promoted within the European Sustainable Nuclear Industrial Initiative (ESNII) between 2010 and 2018:

- **MYRRHA**: a lead-bismuth Accelerator Driven System to demonstrate transmutation of high-level waste in a double strata fuel cycle approach.
- **ASTRID**: a sodium cooled prototype reactor to demonstrate sodium-coolant technology for electricity production in a closed fuel cycle. However the French government sponsoring the project has made in early 2019 strategic decisions which are analyzed in section 3.3.2.
- **ALFRED**: a lead-cooled reactor to demonstrate lead-coolant technology for electricity production in a closed fuel cycle.
- **ALLEGRO**: a gas-cooled reactor to demonstrate electricity production in a closed fuel cycle.

ESNII
European Sustainable
Nuclear Industrial Initiative

ESNII Program Prioritization

In 2019, ESNII analyzed the status of the ESNII project and system maturity based on the prioritization criteria of technology readiness level and the advancement or impetus of European projects. MYRRHA was judged as is the most advanced ESNII project having the highest potential to reach full maturity, thanks to the increased technology level in liquid lead-bismuth technology, pre-licensing activities and the continued strong support of the Belgian Government. It is however a research and development project. MYRRHA could be followed by the construction of an industrial initiative: an Advanced Lead cooled Fast Reactor European Demonstrator (ALFRED), having SMR oriented features. With regard to the development of fast reactor technologies in Europe, sodium reactor technology has achieved a significant degree of maturity. However today, there is not yet sufficient state support to realize a demonstrator for this technology in the short-term. Sodium fast reactor R&D will therefore continue in Europe in the medium term. Finally, the Gas Fast Reactor technology concept still needs basic design and R&D efforts to demonstrate viability..

Funding resources

R&D projects in support of prototype construction are mostly supported by national programs and European Commission calls for proposals. Industry is currently committed through in-kind contribution as well as funding of R&D national laboratory programs. Long-term R&D requested for the deployment of ESNII systems is expected to come from EC and public – public partnership, since the realization of such prototypes and demonstrators aims at implementing, in a pre-commercial and operational environment, the last stage of an R&D program for future technology deployment. For the period 2015–2030, the overall cost for ESNII R&D and for prototype, research facility and demonstrator construction is evaluated at around €10 – 15 billion, including a MOX fuel fabrication plant for the projects that will be using it, i.e. MYRRHA and ALFRED. More specifically, the Belgian Federal Government allocated 558 M€ for the period 2019 – 2038 for the realization of MYRRHA.

NC2I

The EU currently generates 11.2% of its electricity using cogeneration. In Latvia and Denmark, cogeneration contributes around 45% of total electricity generation. Today, cogeneration installations are dedicated to individual buildings, industrial factory and district heating systems. In Europe there are about 5000 district heating systems, which are mainly located in the Northern and Eastern part of Europe. The market share of district heat is about 10% of the heating market.

The main objective of nuclear co-generation is to develop its application for the large and growing global market of non-electrical applications, for instance:

- ✓ District heating/cooling;
- ✓ Seawater desalination;
- ✓ Industrial heat supply;
- ✓ Hydrogen production.

Achieving these goals requires significant changes in the design philosophy of nuclear reactors. The main criterion is the temperature at which the energy is consumed. However, another important parameter is the amount of heat consumed by each of the processes. In Europe, individual industrial processes require less than a few hundred MWth. The most favourable approach to nuclear electricity cogeneration is therefore a reactor of small to medium power. HTGRs are well suited, with power ranges up to 600 MWth, very good safety parameters, and ability to provide heat at temperatures utilized by the “steam” market.

While many HTGR technology challenges have been addressed, the main issue hampering a broad market introduction of nuclear cogeneration is a lack of demonstrated technical and commercial success with applications up to 600°C, and beyond several tens of MWth.

The approach toward a broad implementation of nuclear cogeneration should therefore concentrate on developing and building demonstrator(s), which would serve as prototype for the next units, as well as examples of commercial success to follow.

High temperature markets are promising given the potential to displace large quantities of energy generated by fossil fuels.

NC2I program prioritization

Prioritization of the NC2I R&D program is defined as supporting the construction of an HTGR demonstrator plant featuring a cogeneration facility for steam supply early enough to bring a contribution to the European Green Deal Objective.

In Europe, typical large industrial sites require a heat supply capacity between 100-1000 MWth with an equally wide range of electricity supply. In the past, nuclear cogeneration projects were limited to steam delivery at approximatively 240°C and below, mainly for paper factories, district heating or other applications in this temperature range.

The demonstrator construction program would have to consist of several steps:

- ✓ Detailed design of the reactor;
- ✓ Site selection and siting studies;
- ✓ Licensing the demonstrator on the designated site in accordance with both nuclear and process heat system regulations;
- ✓ Financial commitment of industry and public stakeholders;
- ✓ Construction of prototype and supply of critical components;
- ✓ Demonstration plant start-up, tests and subsequent operation.

To accelerate demonstration, the HTGR could be operated on core outlet temperatures around 750°C, which is largely sufficient for the targeted large process steam market up to 600°C. As a result, the demonstration plant would be converted into a marketable commercial solution with large domestic and export potential.

In the longer term, it is expected to venture into operation at higher temperatures; likewise the German and Japanese test reactors (AVR and HTTR) have been operated for extended time at helium outlet temperatures of 950°C. In the future, another demonstration plant using very high temperature materials and coupled to a very high temperature process heat application would probably need to be constructed.

Considering the options for a demonstration of high temperature nuclear cogeneration in Europe, NC2I believes Poland to be the most likely candidate. Since 2016, Poland has undertaken intensive preparatory work aimed at implementing solutions based on high-temperature reactors for Polish and European industry. These goals have been included in the Responsible Development Strategy (the so-called Morawiecki Plan). The result of the preparatory work was an analysis by the Ministry of Energy regarding the implementation of high-temperature reactors in the Polish industry, a result of which high-temperature reactors cooled with helium gas were identified as the target solution. In 2019, the Gospostrateg project financed from public funds began, which aims to prepare a legal framework and technical environment enabling the implementation of HTGR. In January 2020, the Ministry of Science and Higher Education decided to enter a European experimental high-temperature helium gas cooled nuclear reactor project, EUHTER, including it on a list of Polish strategic research infrastructures. EUTHER is targeted at paving the way to the deployment of HTGR for industrial cogeneration in Poland. NC2I focused its efforts on the support of the Polish project and in particular proposed the main design options for a HTGR adapted to the needs of Polish industry in the H2020 GEMINI+ project.

Funding resources

The major obstacles to implementation of nuclear cogeneration are the costs of design and construction of the prototype, and the acceptance by heat using industries of being supplied by a nuclear reactor, with the subsequent licensing and public acceptance challenges. The key for establishing the landscape of the HTGR's industrial usage is the first demonstration with a prototype reactor coupled to an industrial process heat application in the near future.

Engineering, construction and commissioning are the most important costs for each prototype nuclear plant. A consortium formed from various partners could be envisioned as follows:

- Technology Supplier – design of the prototype and licensing the demonstrator;
- Constructor (can be the same company as the technology supplier) - responsibility for the construction of the prototype;
- R&D centers – assistance with technical matters;
- Heat end-user – interest in an affordable and stable heat source;
- Demonstrator operator – interest in an affordable and stable energy source;
- Financial institutions (national and international) - providing appropriate financial backing for prototype.

The project can proceed in two steps. The first step will be specifically developing the prototype and predicting potential obstacles and in the second step, the prototype will be licensed and constructed. In each case, the consortium may consist of different members.

2.3.3 Integrated vision and global deployment for SNETP program

Given the lead time required for the industrial deployment of different nuclear systems, an overlapping period is expected between existing Generation II-III operations, Generation III new build, and other potential new systems as well as the penetration of nuclear energy in the market of non-electric energy. A common strategic agenda helps to identify technical and cross cutting issues which should be resolved to facilitate a smooth integration of different nuclear systems (towards a potential switch from one technology to another). The definition of a common research agenda is will cross the boundaries of SNETP, facilitating engagement with other stakeholders and sectors.

Transverse issues and clustering

For optimizing R&D project implementation of the three SNETP pillars, synergies between the nuclear systems and with other energy technology platforms should be identified and refined.

- Early stage technology development opens routes for the identification of common trunks for Generation II, III, and IV and cogeneration application in areas such as: material; structural integrity; manufacturing and assembly technology; instrumentation and control; digitalization; cyber-security;
- Research infrastructures are essential for the validation and qualification of technology development;
- Fuel cycle and waste management is an essential component of any nuclear system deployment;
- Methods for facilitating nuclear systems construction should be shared among

the SNETP pillars recognising the dynamic environment where technology is continuously improving, policy regulation is being updated, and safety requirements are becoming more and more stringent;

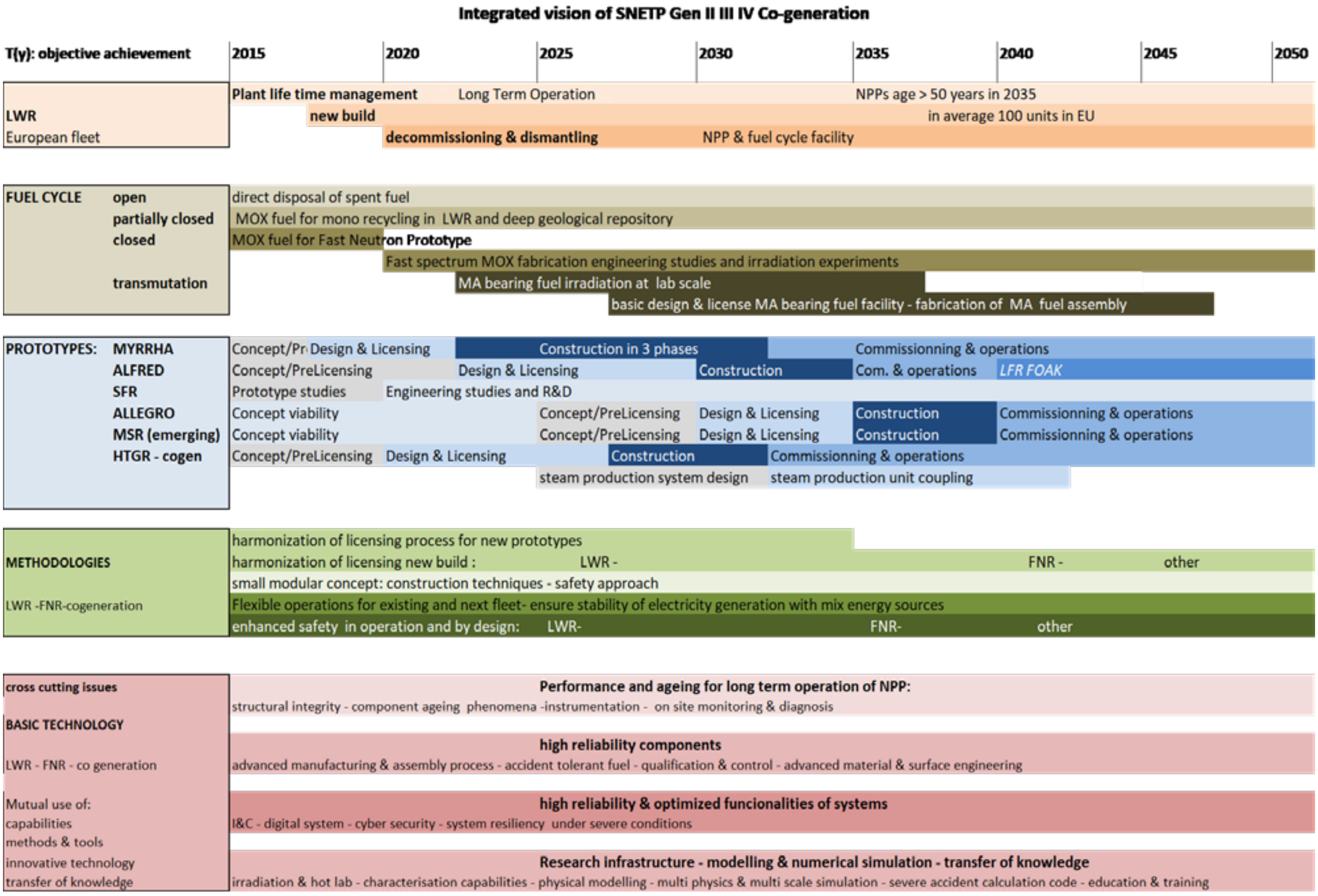
- Finally, common to all nuclear technologies is the crucial aspect of engagement with other energy technologies in view of identifying the best strategy to achieve climate-neutrality by 2050, as well as with civil society at large. It is essential to promote nuclear energy as a friendly source, on the same footing as renewables as part of the solution to tackle climate change;
- Commonalities with other industrial sectors shall be envisaged especially concerning innovation in various domains such as digital, materials, etc;
- Win-Win collaboration at the international level shall be reinforced to strengthen the leadership position of the European R&D&I in the nuclear fission sector.

SNETP tentative roadmap with an integrated vision

A global vision highlighting nuclear product evolution over the time scale 2015-2050, and considering the European Green Deal plan, reinforcing the need for nuclear capacity to play its role in the energy mix portfolio that facilitates a sustainable path towards the CO2-neutrality goal by 2050. The development of nuclear is driven by the high-level objective of the EU concerning the climate change: if global warming is to be curbed by 2050, a reinforcement of nuclear in the energy mix and its penetration in non-electric energy uses are needed as soon as possible. Different layers have been identified with milestones to be reached. Common trunks between Generation II, III, and IV and cogeneration have therefore been identified in these layers to reinforce the synergies between the SNETP pillars:

- ✓ European current fleet;
- ✓ Prototype construction;
- ✓ Fuel cycle and waste management;
- ✓ Analysis methodologies;
- ✓ Basic technology.

The SNETP deployment strategy is illustrated in the updated roadmap below which was firstly introduced and explained in detail in SNETP (2015), and which seeks to illustrate the consistent connection between the industrial nuclear sector, the technology R&D program (from laboratory scale to prototype construction), transverse methods in support, and the time to achieve these objectives.



Light water reactors (Gen II) form most of the current European fleet, now 30 years old on average, they are expected to be renewed with a potential peak of activity between 2035 – 2050. This identifies an early period prioritizing long-term operation-related R&D projects followed by new build (Gen III +) which should benefit from innovation and progress made in various technical domains.

Prototypes of Gen IV technology are being studied, with different maturity levels, as well as an HTGR cogeneration demonstration plant. For MYRRHA, planning for construction of the facility was discussed with the Belgian Government with a proposed construction period of 2027 - 2033. For the other facilities, ALFRED demonstrator and HTGR cogeneration demonstrator, the planning will primarily depend on securing the appropriate financing. ALLEGRO and an MSR prototype (for which the timeline in Europe is inspired by GIF (2014), in line with the announcement of the Dutch Thorizon initiative and conservative with respect to the British Moltex and Danish Seaborg initiatives which aim at construction of a reactor by 2030, be it not in Europe necessarily) the planning will depend on the outcome of the feasibility phase.

Commissioning of new prototypes should be supported by harmonization of the licensing process. Likewise, MOX fuel processing and re-fabrication, i.e. multi recycling for fast neutron reactors, needs to be aligned with prototype operations. Transmutation in fast neutron reactors as an option for waste management requires minor actinide-bearing fuel fabrication and irradiation at reasonable scale.

In Europe, the construction of MYRRHA, the execution of Sodium Fast Reactor engineering studies and the execution of Lead Fast Reactor Engineering studies, followed by ALFRED construction will provide sound experience to prepare the industrial deployment of LFR technology around 2040 and SFR technology later in the second half of the 21st century.

Methodologies dealing with licensing and safety assessment could strengthen interfaces between the different nuclear systems and assist with the suitable integration of different energy sources in the European mix. Harmonized licensing process for LWR new build should be ready before the expected peak around 2040. Construction techniques and innovative design developed for small modular concepts should benefit all reactor systems. Considering the rapid evolution of the future electrical landscape, with an increasing share of renewables in the electricity market, nuclear power generation will become necessary to ensure a stable system across Europe. The need for continuous domestic and industrial heat, and the expected penetration of hydrogen in the energy system, impose a rapid deployment requirement for all low-carbon technologies to answer the growing demand of energy at the global level – but particularly in Europe to replace fossil fuels.

Finally, creation, enrichment, mutual use and transfer of knowledge and expertise gained in different technologies are prerequisite to achieve high reliability, performance and optimized functionality of components and systems for Generation II III, and IV, for generating electricity or cogeneration. While keeping the European skills, competences and industrial capacities, SNETP envisions reinforcement of leadership of the European industry in the nuclear field by encouraging, supporting and implementing cross-sectorial innovation across the whole value chain.

> ***Considering the rapid evolution of the future electrical landscape, with an increasing share of renewables in the electricity market, nuclear power generation will become necessary to ensure a stable system across Europe.***

3. REACTOR TECHNOLOGY

3.1 Operation and Construction

3.1.1 Objectives and Motivation

Low-cost baseload electricity supply is a critical enabler of economic and social development. According to IAEA (2019), 449 civil power reactors are in operation and 52 reactors are under construction worldwide as of 2019. Construction mainly takes place in China, India and Russia. Nuclear power has played a key role in delivering such supply for decades in many countries and will continue to do so in the years to come. Maximum and efficient utilization of the existing portfolio of nuclear reactors is therefore a priority in Europe.

The current global fleet was developed with plant design lives that were typically either 30 or 40 years. The economics of nuclear are characterized by low and stable operating costs, resulting from the low proportion of fuel cost in the total cost structure. This has enabled nuclear plants to supply reliable, competitive and low-carbon baseload power. Once built and commissioned, and assuming a good operational performance, nuclear power plants should be able to carry out this indispensable role for the long term. With high fixed costs and low running costs, average electricity costs for nuclear plants fall substantially with increased output. It is therefore vital for nuclear operators to achieve high plant capacity factors for long-term operation.

To reduce operation and maintenance costs, the nuclear industry has taken advantage of digital technologies to automate much of its testing and maintenance activities. In particular, the industry has begun to transition from traditional time-directed, hands-on, and reactive maintenance procedures to condition-based, risk-informed, and automated maintenance strategies. This is partly because the current generation of nuclear power plants has passed its mid-life, and increased monitoring of plant health is critical to their continued safe operation. This is especially true now that license renewal of nuclear power plants has accelerated, allowing some plants to operate up to 60 years or more. Furthermore, many utilities are maximizing their power output through uprating projects and retrofits. This puts additional demand and more stress on plant equipment such as the instrumentation and control (I&C) systems and the reactor internal components making them more vulnerable to the effects of aging, degradation, and failure.

> ***The economics of nuclear are characterized by low and stable operating costs, resulting from the low proportion of fuel cost in the total cost structure. This has enabled nuclear plants to supply reliable, competitive and low-carbon baseload power.***

The components, systems, and structures in NPPs are in general categorized in two classes: active or passive. Active components are managed under a maintenance regime, and this covers items such as pumps, motors, valves, and compressors. Passive components, which include the reactor pressure vessel, piping, core internal components, the containment structure, and cables, are managed using in-service inspections (ISI) performed in the context of an aging management plan (AMP). Degradation found under an ISI program is managed through mitigative actions, changes in designs, and repair or replacement of degraded components. This reactive, find and fix, approach has maintained the safety of operating reactors but it is becoming increasingly expensive as plants age. Attention is now moving to consider the potential for more proactive management of both active and passive components.

For passive component assessment, researchers have investigated NDE technologies that are sensitive

3

to degradation precursors due to mechanical fatigue, thermal aging, and radiation effects. Most research to date has resulted in empirical relationships between precursor phenomena and NDE measurement parameters. More work is needed to fully understand the separate effects of multiple microstructural phenomena on NDE signals and to develop physical models correlating microstructural changes, induced by aging, to macroscopic NDE measurements.

Quantification of uncertainty through the measurement and prediction process is essential to bounding the confidence of diagnostic assessments and predictions. Uncertainties are associated with the NDE measurements, including interpretations of the degree of damage, stressor history, future stressors, and the models used to integrate factors and extrapolate and bound predictions moving forward in time.

3.1.2 State-of-the-art and Challenges

Owners of nuclear power plants currently operating in deregulated competitive markets are under pressure to reduce operation cost to be more competitive with other energy production options. To recover huge initial investment cost and to maintain necessary level of profitability it is reasonable to prolong operation of plants (LTO) where it is feasible and without compromising safety and security. Along with traditional safety and reliability parameters, economic and financial factors need to be taken into account given new perspectives that are incomparable with former regulated markets where utilities provided complex service with inclusion of all reasonable costs. Another aspect is that nuclear power plants will be operated in markets with increasing number of decentralized and variable renewable sources (weather condition derived energy production) and therefore flexibility (higher manoeuvrability) of nuclear power plants will be important.

It should be noted that operators of nuclear power plants continually improve their assets by a variety of measures, notably:

- power uprate (e.g. design reserves utilization, efficiency);
- optimization of maintenance and outages;
- upgrade and more efficient utilization of nuclear fuel (e.g. increased cycle length, enrichment, burn-up, reload patterns);
- flexibility of operation (e.g. load-following mode);
- impact of Gridcodes and integration of nuclear plants in the energy mix (Rioual et al., 2017);
- impact of new equipment in power plants with respect to:
    - large equipment
    - electrical distribution network

- instrumentation
- stability
- development of new tools

Improvements in operation are also realized as a result of inputs from missions and peer reviews that are focused mainly on safety, but that also take into account aspects of operation. The most impactful reviews are organized under the auspices of the IAEA and the World Association of Nuclear Operators (WANO). The WANO mission is to maximise reliability and safety worldwide through common efforts in assessment, benchmarking, mutual support, information exchange and use of best practice. Areas contributing to improvement of reactor and nuclear power plant operation can be divided into management, organizational and human performance measures on the one hand, and technical measures on the other.

> *The WANO mission is to maximise reliability and safety worldwide through common efforts in assessment, benchmarking, mutual support, information exchange and use of best practice.*

Human and organizational factors are key subjects of analysis made with the aim to improve safety, performance and efficiency characteristics of nuclear power plant operation. After the Fukushima accident, the focus of studies has moved towards the importance of the preparedness for emergency management, but the area of prevention also needs attention (e.g. safety culture, safety versus efficiency, and impact of automation). Important challenges are to strengthen the objectivity of safety judgments by using methods of risk-oriented decision making to strengthen human reliability, to improve the effectiveness of safety provisions, to harmonize operational principles across Europe and to minimize the negative impacts of complexity on operation and safety. Since organizational safety culture and operating practices strongly influence safety, new research should help in defining of the conditions required for ensuring the robustness of organizations in charge of operating NPPs, based on a deep understanding of work practices and safety culture.

Specific challenge represents higher level of **flexibility** (non-baseload operation) as a reaction to market conditions with increasing portion of variable renewables. NPPs should be prepared to participate in the trading of electricity in quite complex conditions and provide various ancillary services such as frequency control, load following or reactive power control.

Surveillance, diagnostics and monitoring techniques generate information in order to provide better knowledge about condition of material, equipment and systems. These are prerequisites for life-time management of, increase of reliability, minimization of failures and optimized maintenance. Systems, structures and components of a nuclear plant could be divided into two general classes: those that are active components (such as pumps, motors, turbo-generators, valves, compressors, sensors and actuators) and those that are passive components (such as the reactor vessel, piping, reactor internals, containment structure, cables). For active components (e.g. rotating machinery), there are plenty of SDP techniques, with the exception of prognostics, that are proven and routinely used. For passive components, periodic in-service inspections are implemented in accordance with ageing management plans, using non-destructive examination techniques, such as eddy current testing and ultrasonic wave measurements (IAEA, 2013).

Advanced materials are needed for construction of components and systems with improved functionalities and reliability, to be replaced during maintenance and upgrade (also to be prepared to LTO), or to be prepared for new generation of NPPs. A first issue concerns the development of new reactor materials which encompasses new steel grades with improved properties, the study of surfaces engineering techniques such as machining, heat treatment, and peening, to mitigate stress corrosion cracking and fatigue (see also section 5.2).

More innovative solutions are to be investigated in the area of coatings (mainly sprays), multilayers or composite materials as well as surface engineering improvements (e.g. heat treatment, peening) giving to materials improved characteristics (corrosion, resistance to load,..).

Recent studies have shown evidence that combining different materials and **manufacturing routes** may result in multi-functional materials. Large power generation components are commonly fabricated using conventional methods, such as forging, casting and grinding as a finishing operation. Recent research has highlighted the major attributes of powder metallurgy technology, especially high isostatic pressing and additive manufacturing with, for this latter route, different emerging technologies: 3D printing, laser deposition, cold spray. New manufacturing methods are also considered for improved assembly technologies: advanced welding (electron beam…) or bimetallic junctions by high isostatic pressing. Fabrication procedures such as stable thermo-mechanical treatments are also of use, especially in view of improving the properties of existing classes of steels.

Associated with these scientific and technological developments, improvement of computational tools is a challenging field in order to predict materials microstructure, metallurgical properties, residual stresses, deformation and macroscopic behaviour of this newly elaborated reactor components. Important work regarding codification of these new materials/technologies is likely to be required.

Digital transformation represents one of the most important challenges to nuclear power plants operation as for industry, services and society in general (see section 5.1). Many activities worldwide are focused on the digitalization of nuclear plant activities. "Digital" includes the use or virtual (3D) or augmented reality (virtualization of real world with added information), the use of most advanced data analytics techniques such as machine learning, neural network learning and other forms of artificial intelligence, implementation of digital twins, high level of automation and robotization, and a vast deployment of Internet-of-Things technologies for sensing and control of processes. The final goal is to improve optimization of maintenance and repair of equipment, preparation of outages, training of personnel with to reduce and/or eliminate human failures and on-site assistance to maintenance and operational staff, accessing procedures and technical documentation from portables and wearables devices.

> ***Digital transformation represents one of the most important challenges to nuclear power plants operation as for industry, services and society in general.***

The goal of management of a LWR **core with fuel assemblies** and associated systems is to maximise cycle energy production with minimal fuel cost while maintaining sufficient margins, to relevant improvement of precision of core calculations and better estimation of their uncertainties. Improvements of in core management are currently based on continuous updating of the design and analysis tools, with the aim of achieving higher accuracy with well-established uncertainty evaluation, through a strengthened understanding of the underlying physics and associated modelling requirements, combined with enhanced computational efficiency. This task can be directly translated into large challenges in basic nuclear data, neutronics, material science, thermal hydraulics, fuel fabrication and fuel storage. Coupling all these aspects (multi-physics) with the help of up-to-date advanced software is the driver for replacing the current systems of codes used for simulation of processes related to reactor operation (see also section 5.1). Advanced instrumentation and measurement methods, and efficient signal analysis, can increase reliability, performance and competitiveness.

Water chemistry and low-level waste (LLW) management activities are a main target in optimization of chemical parameters of the primary, secondary and auxiliary cooling systems and in development of optimum technologies for LLW treatment. Water chemistry is one of the most powerful tools that operators can use to improve the lifetime of plant components and systems. Suitably designed water chemistry can significantly reduce operational problems such as corrosion, erosion, and deposition of corrosion products.

Concerns over radiation exposure of workers as well as on the radioactive releases into the environment require constant improvement of processes and technologies for LLW treatment and for conditioning of liquid waste. Priorities are to obtain higher decontamination and volume reduction factors, lower both on-site and off-site processing costs, and reducing solid radioactive waste generation rates.

Radiation protection is a specific area to protect both human beings and the environment against negative impact and/or consequences of ionization radiation. The main goal is to keep the ALARA principles, i.e. to limit the exposure «as low as reasonably achievable». A strong focus on radiation protection has led to the establishment of the CONCERT European Joint Programme integrating effort in individual platforms and associations – MELODI (Multidisciplinary European Low Dose Initiative), NERIS (European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery), ALLIANCE (European Radioecology Alliance Association), EURADOS (European Radiation Dosimetry Group) and EURAMED (European Alliance for Medical Radiation Protection Research) along with activities in social sciences and humanities. Cost effective solutions and application of new tools are in high demand, including more accurate dosimetry. Risk remains in the potential tightening of radiation limits for personnel and the environment leading to further new measures and requirements for new measurement tools.

Apart from the measures mentioned above, others to ensure safe and reliable **long-term operation** under ageing conditions of the plant remain very important. An effective ageing management of systems, structures and components (SSCs) is a key element in plant life management (PLiM) for the safe and reliable long-term operation (LTO) of NPPs. PLiM can be defined as the integration of ageing and economic planning for the purpose of maintaining a high level of safety and optimizing plant performance by dealing successfully with extended life ageing issues, maintenance prioritization, periodic safety reviews, education and training.

LTO for 60 years and beyond necessitates a consistent PLiM programme that includes technical and economic assessment to:

- Maintain a high level of safety;
- Optimize the operation, maintenance and service life of SSCs;
- Maintain an acceptable level of performance;
- Maximize return on investment over the service life of the NPP;
- Provide NPP utilities/owners with the optimum preconditions for achieving the desired LTO.

Although each country and reactor technology may have unique requirements and LTO justification methods, they can be classified in three main categories:

- The periodic safety review method, which is typically used in European member states with unlimited or continuing licences;
- Limited term licence and a licence renewal concept;
- A combination of the previous two approaches.

In all cases, the preparation for a LTO permit application implies the conduction of a thorough ageing management review to establish the current state of critical SSCs and their usage factor for fatigue assessments, in order to determine their fitness for prolonged service to the end of the LTO permit duration.

The equipment in a nuclear power plant must function when called upon with a high level of reliability, based on conservative assumptions and methods, not only for normal operation, but also for anticipated events, transients and accidents as well as postulated events, in other words Design Basis Events (DBE) and Design Basis Accidents (DBA). Furthermore, NPP equipment also needs to function under postulated conditions beyond DBE and DBA. Such postulated conditions are denoted Design Extension Conditions (DEC) and under such conditions may the reliability be shown with realistic assumptions and methods. Equipment in a NPP therefore needs to be environmentally and seismically qualified. LTO of NPPs requires reliable equipment function in all NPP SSCs. This is ensured via appropriate maintenance, replacement and repair strategies through an appropriate PLiM, so that the equipment is able to perform its intended function in a reliable and safe manner throughout its lifetime or intended time of use.

The PLiM analyst needs to look into the past history of the SSCs, making use of all available records, including those generated by on-line monitoring and diagnosis systems, wherever available. On-line monitoring systems, if selected and set-up for the purpose, can provide a precise record of any deviations from the SSC technical specification by recording changes in parameters and variables, such as peak values, Fourier spectra, vibration residues, critical speeds and chemistry values. Monitoring can also provide information on the ageing assessment of SSCs, such as pressure boundary leak tightness, number and entity of pressure and thermal transients and functional anomalies in components. Monitoring systems can also provide information on unaccounted stressors and interference with the functionality of systems and components, including cases such as the inadvertent introduction of loose parts. Data, in the most advanced on-line monitoring systems, are post-processed, and recommendations are automatically issued to help operators optimize the planning of maintenance activities and, in special cases, design upgrades and system improvements can be suggested. On-line monitoring systems allow analysts to follow the equipment behaviour and provide meaningful data for an LTO feasibility analysis.

To address the R&D needs towards long-term operation, various national and international programs have been initiated and major reports and databases developed by both regulators and industries. The international community has also focused on the issue with the IAEA's PLiM committee, OECD-NEA's committee on the Safety of Nuclear Infrastructure (CSNI), European Groups through the NUGENIA association and Euratom program, the Materials Aging Institute in France, proactive management of materials degradation (PMMD) programs in Japan and Korea, and related work in a number of other countries that are all recognizing the challenges faced in extended LTO for NPP.

Past collaborative projects (too many to be listed) have been structured along three main paths:

01 Projects aiming at providing laboratory tests results regarding various degradation mechanisms in order to construct empirical trend curves to support the engineering decisions;

02 Projects aiming at analysing in-service or surveillance programs from various decommissioned or operating reactors both to complemented and to verify the databases;

03 Recently, some projects have been initiated to use the existing experimental knowledge to formulate physically-based predictive models for a specific degradation mechanism.

However, only very few projects are now ongoing to apply the existing knowledge to develop in-service monitoring strategies accompanied with preventive maintenance to predict or mitigate the residual lifetime of some safety related components.

Construction and commissioning of nuclear power plants represent some of the most complex infrastructure projects in human history. Recent projects have experienced huge delays and investment cost overruns (Mochovce, Flammanville and Olkiluoto in Europe; Vogtle and VC Summer in the USA), although some remain on time, schedule and budget (mainly in Asia). Another aspect is the often long preparatory period due to comprehensive approval processes (national laws, international obligations) complemented by extensive public consultations. Potential approaches for keeping the cost plan and time schedule have been analysed recently by the Energy Technologies Institute (ETI, 2018) with the following recommendations (reflecting the UK situation, but results are generally valid):

- Complete plant design prior to construction start;
- Follow contracting best practices;
- Develop multiple units at a single site;
- Develop alignment with labour around nuclear projects;
- Government should encourage systematic application of best practices and cost reduction measures;
- Develop a national program to maximise and incentivise learning;
- Government support to the financing process;
- Regulatory engagement should be reformed to focus on cost-effective safety.

A possible solution to the current challenges with construction of nuclear power plants could be designs for smaller generated thermal power and modular construction techniques.

3.1.3 R&D Topics

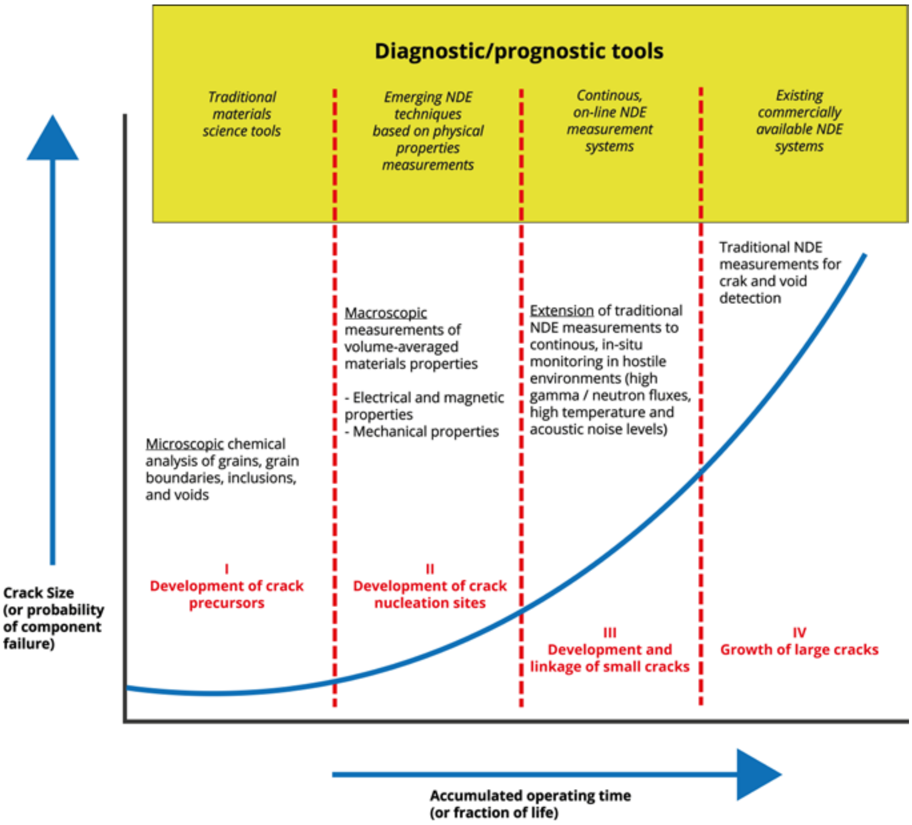
The identification of the SSCs that are subject to ageing is a key issue for plant life management. It is essential to perform analyses for understanding and modelling of the main ageing mechanisms concerning each SSC (potential or encountered). Finally, measures must be set up to justify the integrity of each SSC based on codes & standards, regulations, specifications & guidelines and scientific knowledge of the ageing mechanisms. It is important to realize that SSCs should not only be treated on a structure and component level. The approach should be moving from component based towards system-based design.

Degradation in metallic components

Degradation in metal components in its early stage is characterized by the development of crack nucleation sites and then small cracks, which are below the detectability threshold size of current NDT. Laboratory techniques can be used to study crack initiation. However, in deployed systems the early detection of degradation will increase the probability that corrective actions are timely planned and implemented. Earlier knowledge of degradation also has the potential to provide plant staff with greater flexibility in taking resolutive measures, thereby avoiding failures or leaks, rather than merely delaying or mitigating its negative effects.

The four-stage evolution of degradation in passive components is illustrated in Fig. 1, together with an assessment of the maturity of technologies that are suitable for their identification. Traditional NDE technologies are only sensitive to the most severe stages (stage IV) of degradation, while early degradation (stage I) is typically observable only using recently developed materials science tools. There is a need to investigate phenomena between these two extremes, so as to provide field deployable technologies and assessment methods (theoretical or numerical) that are sensitive to stage II-III degradation.

The development of early-degradation sensitive methods requires the identification of suitable observations that correlate with changes in material condition. Such changes should ideally be local variations in electrical, mechanical, or thermal properties that are detected before initiation of a macro-defect, which could later evolve into material loss or a crack. The measurable property variation should therefore result from microstructural modifications (precursors) that lead to defect formation. Examples include changes in dislocation density, grain size/orientation/shape, precipitation of second phases, and others. For instance, gradual loss of fracture toughness may result from generation of dislocations and voids, or grain boundary segregation preceding failure due to mechanical-, thermal-, or irradiation-induced phenomena. To be useful from a plant aging management perspective, precursors should be detectable and quantifiable using either non-invasive measurements and/or robust predictive numerical tools. This may be achieved by understanding and linking the underlying microstructure property changes to measurable bulk material properties (elastic, magnetic, and electrical). However, for these systems to be effective the influence of the microstructural modifications on measurable bulk mechanical properties, as well as on originating measurable elastic, magnetic or electrical property variations, must be assessed in detail.



Monitoring systems and predictive numerical tools should be in place to reliably follow the SSC ageing process caused by known degradation mechanisms, including:

- Irradiation embrittlement (particularly reactor vessel and its internals);
- Creep;
- Corrosion (water chemistry control);
- Wear;
- Fatigue;
- Flow accelerated corrosion and environmentally assisted corrosion, wall thinning of housings and piping (on-line detectors);
- Elasto-plastic thermal deformation phenomena including residual stresses.

Other parameters that need to be monitored include vibrations and thermal stratification (thermocouples and dilatometers).

Special attention should be paid to stress corrosion cracking of steam generator tubes from the safety and economic point of view for LTO. Critical components often difficult access, such as certain RPV base metal sections, reactor supports and reactor structures and other components not included in normal in-service inspection (ISI) programmes, such as buried pipes and underground pipes, should also be included in ageing evaluation for LTO.

One of the challenges then becomes detecting and characterizing small local changes from among natural variability in a nominally homogeneous material using a modest number of sensors to interrogate critical regions. This challenge can be thought of in terms of determining what to measure, how to measure it, where to measure it, and how many measurements to make, all using sensors and instrumentation that will not be significantly impacted or degraded by the operating environment (temperatures, radiation, and chemistry) during extended periods. Any measurement on-site will have to be thoroughly validated, calibrated and qualified. In addition, progress must be made regarding the on-time analysis of the huge amount of data yielding from the automatic and in-situ measurement of all implemented sensors.

Secondly, diagnostics and monitoring simulation tools that can greatly increase ageing management efficiency have to be developed based on the physical understanding of underlying degradation mechanisms. This challenge necessitates an in-depth knowledge of the environmental stressors (load, temperature, water chemistry, irradiation, …), the material properties as well as a profound experimental validation programs at appropriate time and scale for each ageing mechanism.

The main challenge is to develop multi-scale and multi-physics methodologies (see also section 5.1) that take simultaneously into account the load history experienced by any and each critical component during its previous service lifetime and all known and properly assessed ageing induced degradation mechanisms to predict the reliability limits of any components under flexible operating conditions.

Some topics that need further R&D are:

- Adapt existing codes & standards and methodologies to specific operating conditions (e.g. LTO, seismic loading) or creation of new methodologies;
- Deepen the knowledge of degradation mechanisms and their possible impact on the integrity of SSCs;
- Treatment of secondary and residual stresses (including elastic follow-up, crack closure and load history effects);
- Treatment of non-crack like defects (corrosion, thinning, pitting, erosion, flow induced corrosion, crevices);
- Fracture mechanics for thin sections;
- Integrity of RPV internals for long-term operation;
- Benchmarking of safety assessment methodologies including comparison of outputs from deterministic versus probabilistic methods and integration into the safety assessment;
- Validated models for the assessment of structural integrity of in-vessel components under high doses of irradiation.

Concrete structures

Typical safety-related concrete structures contained in LWR plants may be grouped into four general categories: primary containments, containment internal structures, secondary containments/reactor buildings, and other structures. Primary containment structures have significant safety responsibilities including serving as a final barrier to the release of radionuclides, providing protection from severe external anomalies such as missile attacks or natural disasters, providing shielding for the external environment from radiation. As a consequence, primary containment structures must satisfy functional requirements for structural integrity and leak tightness. It is necessary to understand the relevant aging mechanisms, their impact on the lifetime of the NPPs, and the adequacy of aging management plans for identifying and mitigating the effects of primary containment degradation.

A variety of phenomena can compromise the functional integrity of concrete structures, including aging degradation, collapse of soils under the raft of the nuclear island which impacts load distribution, seismic activity, and long-term or transient fluctuations in pressures and temperatures during an incident. Leak tightness can be compromised by degradation of welds and seals at joints or through-thickness corrosion of liner plates. Structural integrity is impacted by many forms of degradation associated with both the cement-aggregate mixture and supplemental metallic hardware. The porosity and permeability of the concrete significantly influences susceptibility to degradation through impact on transport of moisture and chemical species through the interior of the member. Degradation of the cement-aggregate mixture can occur by chemical or physical attack, which ultimately manifests as cracking and loss of strength. Some forms of chemical attack include alkali-silica reactions, carbonation, and sulphate attack. Examples of physical attack include freeze/thaw cycles, shrinkage, creep, and drying. Corrosion of metallic hardware embedded in the concrete can lead to cracking in the concrete. Loss of tension in the tendon system is a concern associated with pre-stressed containments and can occur by shrinkage or creep of the concrete, tendon relaxation, or corrosion of tendon cables and anchorage hardware.

Concrete structure degradation is a function of many factors, including constituent materials, location (e.g. coastal or inland), climatic conditions (e.g. temperature and moisture) and the presence of external agents (e.g. aggressive ionic species). As structures age, incidences of degradation, primarily related to environmental effects, increase.

In addition to the development and assessment of the reliability of NDE methods applicable to the various type/location of concrete structure, a robust modelling strategy will have to be deployed using the following enablers:

- Using decommissioned plants to further compile material data and evaluate long-term concrete performance in an NPP environment;
- Evaluation of long-term effects of temperature and radiation;
- Developing damage models and acceptance criteria;
- Non-intrusive methods for inspection of heavily reinforced thick-walled concrete structures and basemats;
- Inspection methods for metallic pressure boundary components including containment liner backsides;
- Utilization of reliability theory to address time dependence changes in structures to demonstrate operability and to estimate end of life;
- Applying probabilistic modelling of component performance to provide risk based criteria to evaluate ageing impacts on structural capacity;
- Determining impacts of refuelling cavity and spent-fuel bay leakage on concrete and embedded steel;
- Development of 'first principle' accurate models to allow for interpolation and extrapolation to stringent conditions.

Cable condition monitoring

Cables are a part of power, instrumentation, control, and communication circuits in NPPs and are essential to both normal and post-accident plant operations. Thousands of kilometres of cables, of a variety of classes, are routed throughout NPPs. Most cables were selected and tested to have a nominal 40-year life. However, LTO is now seeking operation to 60 and even 80 years. In many cases, cables are difficult and expensive to replace. It has even been suggested that it is the economics of cable replacement that could be the determining factor in the economic assessment for the feasibility of plant LTO.

The aging degradation of a cable will be governed by the polymeric system, environmental conditions, and the time scale for which age-inducing stressors are applied. Exposure to high temperatures, moisture, and radiation are key aging stressors for cables. Polymeric insulation and jacket materials can embrittle with sufficient exposure to high temperature and radiation while moisture intrusion can reduce the dielectric integrity of the cable. Exposure of cables to boric acid and mechanical vibrations are also potential ageing factors. In addition to the main cable body, splices and connectors can also be potential locations for degradation and failure.

Localized degradation ("hot spots") can disrupt the function of the entire cable. Thus, consideration of cable architecture, connectors, potential environmental stressors, hot spot phenomena, and the desire to perform measurements in-situ impose a complex set of requirements on cable condition monitoring systems. Condition assessment techniques are generally visual, mechanical, chemical, or electrical in nature. Visual, mechanical, and chemical techniques can provide detailed characterizations of damage but are often localized or destructive in nature. Further, in-situ evaluations in extreme environments, such as within containment, are unlikely if sampling requires direct human interaction. Electrical techniques can sample larger sections of cable, they are non-destructive, and some techniques can be performed online. However, electrical techniques are most sensitive to damage in the conductor and are limited in their ability to characterize damage prior to a failure that impacts electrical function. The application of several condition monitoring techniques is often necessary to form a comprehensive assessment of cable condition. Thus, efforts should continue in the development of in-situ online cable monitoring tools that are able to provide a more holistic assessment of cable condition.

Concluding remarks

New tools and new methods are needed to improve structural health monitoring for LTO:

- ✓ Knowledge on behaviour at different scales (materials, specimen, real structures);
- ✓ Non-Destructive Tests / monitoring devices;
- ✓ Methods to combine all the records and use them in predictive modelling to build a relevant diagnosis (digital twins).

3.2 In-Service Inspection, Qualification and Non-Destructive Examination

3.2.1 Objectives and Motivation

ENIQ
European Network for
Inspection & Qualification
NUGENIA Technical Area 8

The European Network for Inspection and Qualification (ENIQ) deals with the reliability and effectiveness of non-destructive testing (NDT) for nuclear power plants (NPP) and is a network driven by European nuclear utilities working mainly in the areas of qualification of Non Destructive Testing (NDT) systems and risk-informed in-service inspection (RI-ISI). Since its establishment in 1992, ENIQ has performed two benchmark studies and has issued more than 60 documents. Among them are recommended practices, technical reports, discussion documents / position papers, the "European Methodology for Qualification of Non-Destructive Testing" (often referred to as the ENIQ Methodology) and the "ENIQ Framework Document for Risk-Informed In-Service-Inspection". ENIQ is recognised as one of the main contributors to today's global qualification guidelines for ISI.

+60 **documents published since 1992**

ENIQ has two sub-areas in which the technical work is performed, the sub area for qualification, and the sub area for inspection effectiveness. Their members come from utilities, ISI vendors, qualification bodies and research organisations in Europe with additional members from Canada, Japan and the USA. The ENIQ steering committee provides oversight and is the decision-making body of ENIQ. Its members come from utilities of EU member states, Switzerland and the UK plus observers from Canada, Japan, USA and the leaders of the two sub-areas. In 2010 ENIQ was integrated into NUGENIA, becoming Technical Area 8 of NUGENIA.

By coordinating expertise and resources, ENIQ aims at supporting licensees (utilities) and stakeholders in:

- Addressing issues where the practice and implementation of NDT will ensure the safe and reliable operation of NPPs through inspection qualification, the application of RI approaches, and other processes;
- Providing recommendations and guidance to optimise and harmonise processes;
- Continually improving the processes for inspection qualification and RI-ISI for increased effectiveness and efficiency;
- Responding to the new challenges resulting from plant life extension (PLEX) and new build;
- Promoting ENIQ approaches outside Europe and in non-nuclear industries.

3.2.2 State-of-the-art and Challenges

NDT Qualification

The ENIQ Methodology is established as one of the main contributors to providing assurance that NDT of nuclear safety critical components is fit for purpose. This approach assembles theoretical and experimental evidence and combines this with formal practical demonstrations to ensure that utility specific performance objectives are met. As such, ENIQ has always provided and continues to provide leadership on qualification state-of-the-art, creating the first qualification methodology based on technical justifications, issuing ENIQ recommended practices and carrying out pilot studies.

The ENIQ sub area for qualification is responsible for having developed the inspection qualification methodology that is now being used as a basis for all European LWRs and for CANDU type reactors in Canada. The ENIQ inspection qualification methodology is also acknowledged by the IAEA as recommended practice to be followed for nuclear inspection qualification. Recently the sub area for qualification fully revised the European methodology for qualification of Non-Destructive Testing, the ENIQ glossary of terms and all ENIQ recommended practices related to inspection qualification. Currently the sub area for qualification is involved in a number of projects and preparing new ones, aligned with the R&D and harmonization priorities set out below.

Since the 2013 NUGENIA roadmap, the ENIQ sub area for qualification has performed projects on computed and digital radiography, the mutual recognition of qualifications between countries and the usability of inspection procedures. The latter resulted into a new recommended practice on inspection procedures.

At present, the main challenges for qualification are mutual recognition of qualification approaches between countries and the qualification of new NDT systems such as those based on phased array ultrasonic testing, time of flight diffraction ultrasonic testing and computed radiography. The methodology is considered to be sufficiently flexible to qualify NDT techniques on non-metallic components, such as concrete or high-density polyethylene. The accuracy and validity of NDT inspection simulation software will continue to be an important area of activity due to its increasing role in NDT design and qualification. Looking forward, the application of artificial intelligence and machine learning to NDT systems allowing to handle and to analyze data generated by monitoring systems and the associated challenges this will bring to qualification of processes is another important area of focus for ENIQ. Moreover, the application of “cognitive” sensors that can decide via its own intelligence which signals shall be measured and how to carry out the measurement and continually monitor certain critical components and structures to gather data related to its condition and is another aspect to be taken into account.

Additionally, as industry continues to embrace innovation then it will be necessary that ENIQ is prepared to adapt the qualification process to allow these technologies to be used. For example, virtual flaws and simulated examination environments are on the horizon.

Risk-Informed In-Service Inspection (RI-ISI)

In 2019 ENIQ sub area for inspection effectiveness published the second issue of the ENIQ framework document on RI-ISI. The ENIQ sub area for inspection effectiveness has also developed a series of supporting recommended practices and initiated a number of other work-streams to advance the principles of RI-ISI and maximize the overall risk benefit. Amongst these are recommended practices on the verification and validation of structural reliability models and guidance on the use of expert panels (which were fully revised in 2017) together with discussion documents on the application of RI-ISI to the inspection of reactor pressure vessels and updating of RI-ISI programs. Sub area for inspection effectiveness members were heavily involved in the RISMET benchmark project on RI-ISI that was organized by OECD-NEA. In 2017 the sub area for inspection effectiveness published a technical report on the lessons learned from the application of RI-ISI to European NPP (ENIQ, 2017).

Since the 2013 NUGENIA roadmap, the sub area for inspection effectiveness has completed the

Remote controlled inspection robot
Photo: NRG (2020)

NUGENIA project REDUCE, looking at risk reduction through ISI. The present challenges of RI-ISI are risk informed pre-service inspection for new build and modification of existing plants, as well as RI-ISI for new build in general, establishing acceptance amongst relevant stakeholders of the developed methodologies and extension to a broader scope of components.

Today there are several ways to create an ISI program for an NPP and in the end it should be an efficient program that fulfils national regulatory requirements. The ISI program could be purely a deterministic- or probabilistic program or a combination thereof. Until now most RI-ISI methodologies only cover piping and not other mechanical components of an NPP. Usually, the plant probabilistic safety assessment does not cover all different equipment, so it could be difficult to create a purely probabilistic ISI program. Instead, some rules detailing how to combine these with deterministic results should be developed.

Some regulatory jurisdictions are welcoming of the RI-ISI approach and the benefits of improved focus on high risk components, often accompanied by overall reduction of personnel dose. ENIQ has a fundamental role to assist with education and harmonization of these approaches across jurisdiction within and beyond Europe.

3.2.3 R&D Topics

NDT Qualification

- Position paper / benchmarking for computed radiography qualification, phased array and guided waves ultrasonic testing qualification under ENIQ type methodologies;
- Understand the technical barriers that preclude the transport of qualifications between countries and find methods or procedures on how to overcome these;
- An independent assessment to verify the accuracy of NDT inspection simulation software;
- Evaluation of the reliability of commercially available inspections;
- Maintaining validity of qualification e.g. through equipment obsolescence (potential new best practice);
- Simulated flaw indications for maintaining the proficiency of the operators;
- Harmonisation on the design of practical trials, data collection, data fusion and production of test pieces for qualification of ISI procedures and personnel;
- Inspection considerations for new plant designs (i.e. water-cooled SMRs, Gen IV reactor systems) for a service life of 60 years or beyond;
- Best practices for techniques and procedures for monitoring the performance and health of materials in-service;
- Use of machine learning in support of ISI of NPPs and qualification of machine learning systems;
- Further development and qualification of non-invasive inspection methods for concealed pipework;
- Use of continuous structural health monitoring systems to complement ISI in NPP based on machine learning and “cognitive” sensors to complement ISI;
- Ageing models, fed with data from continuous monitoring and in-service inspections for predictive maintenance (as opposed to scheduled maintenance).

Risk-Informed In-Service Inspection

- Review RI pre-service inspection (PSI) for new build and modifications of existing plants;
- Extension of RI-ISI to all mechanical components, i.e. beyond piping.

3.3 Next Generation of Nuclear Fission Reactors

3.3.1 Objectives and Motivation

To achieve major steps in terms of sustainability (reduced high-level waste production, better use of resources and higher thermal efficiencies), to open the way for high-temperature non-electricity applications, and to achieve flexibility in terms of adaptation to mix with a substantial contribution of intermittent/variable sources, new types of reactors based on other coolant technologies should be envisaged, combined with more advanced fuel cycles. The use of fast reactors in a closed fuel cycle approach will allow a large decrease in natural resource (uranium) consumption, at least by a factor of 50 (more if the use of depleted uranium is considered), allowing therefore a more sustainable implementation of nuclear energy. One of the major concerns of society regarding the implementation of nuclear energy is also the high-level nuclear waste. Fast spectrum reactors with closed fuel cycles will allow a significant reduction in high-level nuclear waste radiotoxicity and volume. Advanced reprocessing and fuel manufacturing techniques are needed to recycle the minor actinides. These advanced reactor technologies could also be deployed as Small Modular Reactors, combining the specific properties of SMRs and advanced coolant technologies.

> ***The use of fast reactors in a closed fuel cycle approach will allow a large decrease in natural resource (uranium) consumption, at least by a factor of 50, allowing therefore a more sustainable implementation of nuclear energy.***

For the transmutation of high-level waste, in a double strata fuel cycle approach, four building blocks need to be addressed:

- ✓ The reprocessing of current spent fuel;
- ✓ The fabrication of dedicated minor actinide containing fuel;
- ✓ The dedicated burning of MA-containing fuel;
- ✓ The reprocessing of these irradiated MA-containing fuel.

Non-electricity production related applications such as hydrogen production, desalination and high-temperature industrial heat applications are envisaged. Though LWR nuclear power plants can address some of the non-electricity needs (desalination, district heating, steam needs on some industrial processes at low temperature (e.g. paper industry), the actual applications have been limited until now. Moreover, most industrial processes require higher temperatures than what LWRs can provide. In the relatively short term, HTGR, could open up industrial process heat applications (chemistry, petrochemistry and in particular the domain of the growing hydrogen production) to nuclear energy. HTGRs are often Small Modular Reactors which rely on proven technology. Test reactors and industrial prototype plants have operated since the beginning of the nuclear era. In the longer term other types of advanced reactors operating at higher temperature than present LWRs, in particular fast reactors, but also HTGR at higher temperatures (VHTR) could contribute.

3.3.2 State-of-the-art and Challenges

Concerning fast reactor technologies, four projects have been promoted within the **European Sustainable Nuclear Industrial Initiative (ESNII)** between 2010 and 2018:

MYRRHA

A lead-bismuth Accelerator Driven System to demonstrate transmutation of high-level waste in a double strata fuel cycle approach.

ASTRID

A sodium cooled prototype reactor to demonstrate the sodium-coolant technology for electricity production in a closed fuel cycle.

ALFRED

A lead-cooled demonstration reactor to demonstrate the lead-coolant technology for electricity production in a closed fuel cycle.

ALLEGRO

A gas-cooled demonstration reactor to demonstrate electricity production in a closed fuel cycle.

With **MYRRHA**, Europe will again operate a flexible fast spectrum research facility in support of the material development of fast reactor technologies or fusion. Since MYRRHA will be conceived as a lead-bismuth cooled Accelerator Driven System, it will be able to demonstrate the ADS technology, thereby allowing the technical feasibility of one of the key components in the double strata strategy for high-level waste transmutation to be evaluated. From 2010-2018, the Belgium government supported the MYRRHA-project with a total special endowment of 100 M€. In 2015, the staged approach for the implementation of MYRRHA was adopted and in September 2018, the Belgium government decided to continue the funding of the MYRRHA-project with 558 M€ covering the needed investments for the construction of the first part the accelerator up to 100 MeV and its target stations (called MINERVA), the design of the extension to 600 MeV and the design of the lead-bismuth cooled reactor, in total 402 M€ for the period 2019-2026, as well as the exploitation costs for MINERVA for the period 2027-2038, being 156 M€. At the same time the Belgian government decided to set up an international non-profit organization for inviting international partners to join the MYRRHA project.

ASTRID was developed to demonstrate Europe‘s capability to master the mature sodium technology with improved safety characteristics as defined by WENRA. The design of ASTRID (600 MWe) integrates operational feedback of past and current reactors. It is seen as a full Generation IV integrated technology prototype. An associated R&D program was performed to accompany and support the development to increase the robustness of this technology, and allow the goals of the 4th generation to be reached, not only on safety and sustainability, but also on economics and proliferation resistance. In the period, 2010-2018, the ASTRID project benefited from a state-support of 650 M€ plus industrial contributions that resulted in a basic design that was thoroughly discussed with the competent safety authorities in a licensing trajectory. Recently, in 2019, the French government however, acknowledging the fact that there was no threat on the availability of affordable uranium before next century, decided to terminate the ASTRID-project and to envisage a much larger horizon for the industrial deployment of fast reactors, namely towards the end of the century. In this context, the large acquired technology base will be maintained both at the European and international level in view of potential future deployment. The French Long-term Energy Plan (“Programmation Pluriannuelle de l’Energie“) promotes the extension of the industrial closed fuel cycle on the basis of MOX fuel in PWR reactors, in particular in the 1300 MW units until 2040 and beyond. The French government has also launched an ambitious R&D program to explore the feasibility of plutonium multi-recycling in EPR2 reactors beyond 2040. The MOX fuel technology both for thermal and fast spectrum reactors will therefore be maintained through industrial developments and long-term R&D. Fast spectrum MOX R&D should include European collaborative projects as well as member states and industry projects.

The **ALFRED** project is conceived to progressively increase the maturity level of the LFR technology through the design, construction and operation of an Advanced LFR European Demonstrator (ALFRED), as part of a pan-European distributed research infrastructure gathering main experimental facilities for the research, development, qualification and demonstration of the LFR technology. ALFRED, serving the role of the European technology demonstrator reactor, will be operated in multiple stages, starting with low temperature conditions, and progressively increasing performances based on gained operational experience, and on new technological options. The R&D will advance in parallel, feeding the demonstration program with the basis for advanced technological choices and design options. The role of ALFRED is an essential step with a two-fold implication: thanks to its SMR-oriented features, it will increase the confidence in LFR technology as a medium-term competitive option for the future Nuclear Power Plants and will demonstrate the LFR technology can fully meet the goals set out by Generation IV International Forum (GIF). The development of ALFRED will largely benefit also from the R&D performed in support to the reactor part of the MYRRHA-project. The ALFRED Project is promoted by the FALCON Consortium, Fostering ALFRED Construction in the Mioveni nuclear platform. In 2017 and 2018, through the signature of strategic governmental documents at local and national level, Romania has strengthened its political commitment for the construction of the demonstration infrastructure.

Whereas both the sodium cooled fast reactor and the lead cooled fast reactor have as primary objective to produce electricity, both could be used for cogeneration. For lead reactors, the outlet temperature is presently limited to minimize the corrosion of some important components. Medium temperature heat applications are however possible based on currently known technologies.

A Gas cooled Fast Reactor (not to be confused with other gas cooled reactors like HTGRs due to completely different implications in terms of core design and safety) has the long-term potential of combining closed fuel cycle capability with high temperature cogeneration of heat and power, provided that a robust safety concept satisfying the present post-Fukushima safety requirements is demonstrated and that suitable materials are found resistant to high temperatures, pressure and irradiation, and the additional advantage of possibly combining Brayton and Rankine cycles for an improved overall efficiency. As such, the GFR can be viewed as a sustainable fast reactor for high temperature process heat production. In this respect the goal is to reduce the industrial consumption of fossil fuels to produce high temperature process heat and hydrogen. However, the feasibility of GFR has still to be demonstrated and for GFR to become an industrial reality, an intermediate objective is the design and construction of a demonstration reactor. A major challenge for this type of reactor is to manage depressurization accidents appropriately. This reactor has been named **ALLEGRO** and its role, apart from being the world's first gas cooled fast reactor, is to demonstrate essentially the GFR specific safety systems. To fulfil the above goals five member states, namely, Hungary, Czech Republic, Slovakia, France, and Poland have set up the "V4G4" Centre of Excellence for ALLEGRO project coordination.

Due to pending issues about the feasibility of the GFR concept in terms of heat removal capabilities in LOCA events and developments needed for the optimal fuel, **HTGR** reactor concepts are considered a more realistic competitive option for short/ mid-term deployment. Several EU countries have expressed at ministerial level their support for further development of nuclear high temperature cogeneration, as one of the main objectives of the Nuclear Cogeneration Industrial Initiative (NC2I). Poland, currently a heavy consumer of coal, has undertaken since 2016 intensive preparatory work aimed at implementing solutions based on high-temperature reactors for Polish and European industry and has recently entered a European experimental high-temperature helium gas cooled nuclear reactor project, EUHTER, on the list of Polish strategic research infrastructure (see section 2.3.2). NC2I is supporting the Polish developments through its project GEMINI+ and has proposed further developments to enhance the benefits of nuclear cogeneration, in particular for hydrogen production. The HTGR technology was successfully proven in Germany, the UK and the US, test reactors are currently operated in Japan and China, where an industrial prototype, HTR-PM is in the process of being commissioned.

In the recent EC (2019) report, the **MSR** (thermal or fast spectrum) has been identified as one of the potential radical innovation breakthroughs of the future that may exert a strong impact on global value creation and offer important solutions to societal needs. GIF (2018) comprehensively describes the technological challenges underlying the development of MSRs. These challenges are confirmed by EC (2019) in generic terms. The main challenges for MSR development start from obtaining fundamental knowledge about physical and chemical characterization of molten salt fuel compositions. Supporting deployment of a demonstrator unit, instrumentation and control of liquid salts requires attention, as well as design rule modifications for components, on-site fuel processing and construction of out-of-pile and in-pile test facilities.

3.3.3 R&D Topics

The important technical choice of pelletized fast reactor MOX fuel should lead to the harmonization of fast reactor fuel R&D in Europe, which is not the case in the rest of the international R&D community (GIF) – where metallic and nitride/carbide fuel are also considered. Some fast reactor communities also use MOX fuel compacted using vibration techniques. The comparison of pelletized MOX and compacted MOX at the international level will be a useful exercise.

MYRRHA R&D topics

Because of the maturity that MYRRHA has reached over the past decade, the next main milestones of the project are the construction and commissioning of the first part of the accelerator (MINERVA), bringing the development of the reactor to a level that a detailed engineering design can start and finally obtaining a construction license. These milestones are planned to be realised by the end of 2026. For the former, commissioning of MINERVA should start early in 2025 while for the latter, the Preliminary Safety Assessment Report (PSAR) must be completed by mid-2024 to allow the licensing authorities sufficient time for review. The short and medium term focus of the R&D programme for MYRRHA focussed on supporting the achievement of these milestones. Due to the similar behaviour of the coolant of ALFRED and the common use of pelleted MOX fuel in current European designs for LFR, SFR and MYRRHA it is clear that in principle several synergies can be found. On the other hand, the focus on the PSAR for MYRRHA makes that some of the research will be coolant and design specific.

The R&D programme of MYRRHA is split into several main areas. These include fuel and materials qualification, chemistry control, thermal hydraulics, component tests, accelerator reliability and instrumentation and reactor control. Code validation and safety studies should be mentioned separately since many of the fields mentioned above run across the two latter in the sense that safety and validation touch all aspects of the project and therefore relate to all research fields. Specific topics in research for MYRRHA are detailed below. As usual it should be stressed that this list is not exhaustive and as the work progresses, priorities might change.

Fuel and materials qualification

MYRRHA will use MOX as its driver fuel. This allows to use the vast database that has been built up in previous sodium cooled fast reactor programmes. The R&D work in this field is concentrated on extending the information where needed and re-establishing fuel fabrication. A particular effort is put on MYRRHA (coolant) specific issues such as the fuel-coolant interaction, the failure limits of the fuel pins in transients and corrosion behaviour of the cladding. The latter is one of the main topics of the materials programme. Besides corrosion and erosion studies of the clad material and the structural material of the reactor, also the mechanical properties of the materials in the LBE coolant must be thoroughly investigated. This includes accident conditions and the study of welded joints.

Materials coating to mitigate corrosion is also a relevant topic. However, in view of the rather low operation temperature of MYRRHA and the short deployment time relative to the required qualification time of coatings, the focus should be put on coatings for which an established industrial production procedure exists. Of course, this does not exclude that newly developed solutions are applied in MYRRHA at a later stage. It should also be stressed that proper attention must be paid to QA and standardisation of test procedures since only in this way the work can be used in a licensing process.

Coolant chemistry control

The coolant chemistry control programme of MYRRHA is centred on three main topics. The first is the control of the coolant itself which includes mastering the oxygen concentration but also mass transport and managing impurities. The main source of the latter are corrosion products from the structural materials. The chemical interaction between these, the coolant elements Pb and Bi, and dissolved oxygen, on the one hand and the dissolution, precipitation and deposition kinetics of the reaction products and filtering and removal techniques on the other hand need to be studied. The second main topic encompasses the release and capture of radioactive materials from the reactor system. This involves spallation products from the interaction with the proton beam, activated elements where polonium is the most prominent, and fission products that are potentially released from the fuel pins. Both evaporation and aerosol formation need to be considered as release mechanisms. Capture tests should involve both deposition on reactor vessel surfaces as well as the interaction with dedicated getter materials. It goes without saying that both normal operation as well as accident conditions need to be looked into. The third topic that is related to coolant chemistry control is related to component cleaning and decontamination. This is relevant for the reactor maintenance programme and the eventual decommissioning plan. It should be mentioned here that for both materials and chemistry control, but in particular for the latter, long-term investigations i.e. the investigations for the long-term safe state are important as well.

Thermal hydraulics

The thermal hydraulic research activities for MYYRHA mainly serve as input for code validation although several topics are also related to components tests. The work firstly includes system and pool thermal hydraulics investigating flow patterns and potential flow stagnation, striping and stratification. A further major issue is turbulent heat transfer modelling that is required to gain an optimal reliability of thermal-hydraulic computer simulations of the system, and the study of the secondary side of the cooling system to further improve its modelling. A topic directly related to the safety assessment of MYRRHA is the study of thermal-hydraulic effects of earthquakes and the potential effects of the induced sloshing. Finally, thermal-hydraulics also covers the investigation of the progress of a potential coolant freezing.

Component tests

Because of the novelty of the coolant applied in MYRRHA in comparison with the established light water reactor technology, an important part of the work supporting the design and licensing process is necessarily dedicated to component tests. In this effort operational and safety related behaviour of all important parts of the primary system is studied. The fuel assembly and reactor core obviously form the centre of MYRRHA. The basic task regarding the core is to demonstrate its integrity and coolability in all operational and transient conditions. Furthermore, it is essential to assess the failure risks in accident scenarios. For this purpose, experimental and numerical evaluation is needed of the pressure drop and the vibrations possibly caused by fluid structure interaction. Particular attention must be paid to the heat transfer to the coolant under all circumstances including forced and natural convection, (partial) channel blockage, and pin and fuel assembly deformation. Finally, inter-wrapper flow must be assessed to quantify its contribution to fuel assembly cooling and as an input of the assessment of potential propagation of failure to a neighbouring fuel assembly in some severe accident cases. The safety rods and control rods, which double as redundant and diverse safety rods are essential for the control of the reactor in critical mode and for fast shutdown in emergencies. They perform a safety function and consequently a proper assessment of insertion times, reliability and behaviour in abnormal circumstances, e.g. seismic tests, is paramount. The primary pump and heat exchanger form the core of the cooling system. For the former, because of the high mass flow rate required, the hydraulic design of the pump should at least undergo a proof of principle test. Secondly, key LBE submerged parts need to be looked into which means for example that it is important that the impeller material is sufficiently tested against erosion in the coolant and that submerged bearings are tested under relevant conditions. Regarding the heat exchanger besides the thermal hydraulic behaviour, the integrity under normal operation (e.g. due to flow vibrations) and accident conditions (e.g. tube rupture propagation) needs to be addressed. The fuel handling machine is an innovative component in MYRRHA as the fuel assemblies will be loaded from below the core. As a result, proof of principle and reliability tests of LBE submerged remote handling tool needs to be performed. Before this, tests of basic building blocks of the machine such as bearings, gears, cabling, and springs need to be done. Subsequently proof of principle tests of main components such as the gripper need to be performed and finally an integral operational test.

Accelerator reliability

For an Accelerator Driven System like MYRRHA the accelerator reliability is critical. Parallel to construction of MINERVA, further improvement of the reliability of components of the accelerator and development of a fast fault tolerance recovery scheme is needed.

Instrumentation and reactor control

The work on instrumentation and reactor control involves tests of standard reactor instrumentation that is modified of shows different behaviour because of the LBE coolant. This includes temperature, flow, pressure and level metering, subcriticality monitoring, radiological release monitoring, fuel pin leak detection and impurities monitoring. Reactor control evaluation is based on work performed in a zero-power mock-up of MYRRHA.

Code validation

For a large part of the evaluation and safety assessment of MYRRHA simulation tools are needed since it is impossible to address everything experimentally. Aspects that need to be addressed involve thermal-hydraulics, chemistry, neutronics, mechanical properties or most often, a combination of any of these. As a result, an extensive validation process needs to be carried out where the input for validation should come from existing data and the R&D programmes discussed above. For some aspects, for example in turbulent heat transfer, coolant chemistry, materials and multi-physics modelling, model and code improvement would be relevant as well.

Safety assessment

Safety assessment is obviously crucial part of the licensing progress and must play central role in any step of the development of MYRRHA. For this reason, R&D supports for safety is interwoven in each of the research fields by including investigations covering accident scenarios. In extreme cases, e.g. for severe accidents, additional efforts are needed to cover these as well.

SFR R&D topics

Design and safety studies

The ASTRID project has accumulated a large basis of technological and engineering SFR studies. These studies will be pursued to define a functional description and a sketch of a commercial industrial French Sodium Fast Reactor of 1000 MW, extrapolated from Astrid design. As a complementary approach, SMR designs will be studied to see if and how they can reach economic competitiveness with respect to large scale reactors. Both studies will participate to maintain the skills on SFR reactors and SFR technologies.

Simulation and code validation

As explained in section 5.1.2, the general objective is the continuous improvement of physical models and the integration of these models in multi-physics simulation platforms. Another challenge is uncertainty quantification for the intended field of application i.e. considering nominal and accidental situations, conventional or innovative reactor designs. The strategy is to make the best use of the available experimental databases and to complete them when needed (for instance, ASTRID needs are well identified and should be addressed in the coming years).

For SFR, this work encompasses the following items:

- ✓ the modelling of core multi-scale and multi-physics phenomena: natural circulation of primary sodium taking into account the connection with other circuits (secondary loops, dedicated decay heat systems), core behaviour with sodium boiling taking into account all the phenomena induced by the double-phase flows and the coupling with the neutronics;
- ✓ the modelling of physical phenomena encountered during severe accidents: mechanistic models of corium-sodium interaction (developments based on small-scale experiments and/or by simulating experiments, experimental capacities to be developed), corium behaviour on the core catcher, debris bed coolability, materials interactions, etc;
- ✓ also the accurate assessment of chemical risks:
  - Description of sodium leakage and spray fire, aerosol transfer, loading on the containment, atmospheric release;
  - Modelling of the sodium-water reaction in a steam generator: the evolution of the initial defect, the kinetics and the mechanisms of propagation to neighbouring tubes, induced phenomena such as shock waves and mass transfer.

Fuel and material qualification

The general objective is to increase the knowledge on both the UPuO2 fuel at high burnup (10<BU<20 at%), also the assessment on the in pile behaviour of the austenitic stainless steel as the cladding material.

The strategy is to make the best use of the available experimental mater: analyses of experimental irradiations performed in Phénix should be continued.

More generally, the decommissioning of the Phénix reactor is a good opportunity to get specimens of various materials that were more or less characterised in the former programs (B4C pellets in the control rods, coatings ...) and thus, to increase our knowledge on these materials.

Instrumentation and inspection technics

A challenge is the development of sensors and technics directly operable in the sodium. The following needs are of particular importance:

- velocity measurements with eddy-current flowmeters (primary flow measurements);
- neutron measurement with high temperature fission chamber positioned as close as possible to the core;
- defectometry and target visualization in the

sodium with acoustic sensors.

The development program will address the following items:

- performances and robustness of sensors with program of design, manufacture and test of prototypes; performances should be determined for the whole system: sensor + signal treatment + carrier;
- proof of principle of the carrier innovative equipment.

The program will benefit from the ASTRID developments (specification of needs, operating conditions, experimental platform already existing …).

ALFRED technology topics

For the LFR technology the first priority is still related to the development of strategies and techniques to face the coolant corrosion, especially for higher temperature operation envisaged in the long-term. The present approach is to tackle the topic from multiple sides, including: material developments, coolant chemistry (coolant purification and oxygen control), surface treatments (coatings, double walls etc.). Simulations of coolant- material interaction may play also an important role in the understanding of basic corrosion phenomena and help the identification of new approaches to be object of investigation. Such investigation should obviously be complemented by the verification of the irradiation effect on materials immersed in the lead coolant environment.

Other specific topics of investigation are related to the fuel handling technology and operation (given the high temperature of the "cold" reactor shutdown) as well as In-service inspections and repair (in an opaque, high-temperature and high-density fluid environment). Seismic impact, buoyancy effects and lead-water interaction have been already object of investigations that should be however further pursued, although preliminary results are considered very promising.

Specific topics of interest are related to fuel coolant interaction, retention of fission products in lead (including Polonium behaviour) and severe accident progression and phenomenology. Additional point of interest are also related to operational and maintenance aspects of LFR like the coolant toxicity and lead cleaning process to be developed at industrial level. The implementation of passive safety systems is presently object of projects with the aim to assess system behaviour and expected performances.

It is important to point out that the ALFRED project shares with other European fast reactor initiatives the choice of using MOX fuel for which cross cutting actions should be carried out and leverage on important synergies with other liquid metal based technologies, MYRRHA and ASTRID.

The above description of the main topics of interest for the technology development should be used as a starting point of the activities. In fact only the construction of a demonstrator will be able to raise all the relevant aspects of an industrial project, allowing a real and measurable advancement of the LFR technology.

GFR technology topics

Development of an acceptable fuel system is a key viability issue for the GFR system. It is necessary to develop an initial cladding material that meets the core specifications in terms of length, diameter, surface roughness, apparent ductility, level of leak tightness (including the potential need of a metallic liner on the clad), compatibility with helium coolant (plus impurities), and the anticipated irradiation conditions. The needs include fabrication capacities and material characterization under normal and accidental conditions for fresh and irradiated fuel.

The target criteria are:

- Normal operation clad temperature of 1000°C;
- No fission product release for a clad temperature of 1600°C during a few hours;
- Maintaining the core-cooling capability up to a clad temperature of 2000°C.

The GFR also requires a specific dense fuel element that can withstand very high temperature transients, due to the lack of thermal inertia of the system. Ceramic or refractory metal clad should be selected, developed and qualified. Such a programme requires material properties measurements, selection of different materials, their arrangement and their interaction, out-of and in-pile tests up to qualification, demonstration tests.

Existing calculation tools and nuclear data libraries have to be validated for gas-cooled fast reactor designs. The wide range of validation studies on sodium-cooled fast reactors must be complemented by specific experiments that incorporate the unique aspects of gas-cooled designs, including slightly different spectral conditions, innovative materials and various ceramic materials. In addition some unique abnormal conditions (depressurisation, steam ingress,…) must be considered.

The need to ensure robust decay heat removal (DHR) without external power input, even in depressurised conditions is now regarded as a requirement. Previous concepts used electrical (battery) driven blowers to handle depressurized DHR while there are no diesels in the design that had to accommodate potential flooding, integrity of the electrical infrastructure following an extreme event is still required. Work is required on two fronts; first to reduce the likelihood of full depressurization and second, to increase the autonomy of the DHR system through the use of self-powered systems. While these self-powered systems cannot be considered passive, they do not require any external power input.

Finally, the strategy to deal with severe accidents is to be established.

HTGR technology topics

Given the relatively high technological readiness level of the HTGR as a type of small modular reactor, R&D topics concern chiefly those needs that are related to near-term demonstration and licensing of reactors with a typical coolant outlet temperature of 750-850°C. In the area of computer tools, uncertainties related to fission product transport in the reactor must be further reduced both in operating and accidental situations. Codes and Standards for structural materials need to be completed on the reactor and on the end-user side. For this purpose, a suitable materials database needs to be kept available reliably. The supply chain for materials and components needs to be revived, and manufacturing capability needs to be recovered where necessary. Some components are likely to undergo qualification tests before commissioning thus requiring specific test facilities in combination with a qualification plan. Specific attention should be paid to the manufacturing and qualification of innovative instrumentation to enable the demonstration reactor to draw full benefit from digitalization. Other specific material subjects include for instance thermal insulation material between RPV support struts and concrete, RPV surface tailoring for maximized radiative heat transfer or material for instrumentation to enhance longevity. Importantly, measures to accelerate deployment and cost reduction approaches should be implemented. Examples may be below-grade construction, simplified design or the creation of a competitive supply chain for materials and components along with harmonized licensing.

Being particularly suited for cogeneration, topics encompassing the coupling to a variety of end-user applications are also of importance which implies different heat transfer fluids on the secondary side (steam, gas mixtures, molten salt…) and thus specific novel heat exchangers, valves and pumps. If an HTGR is used in some sort of load following, components need to be adapted to new dynamic requirements. Some cogeneration applications such as thermo-chemical hydrogen production involve aggressive fluids and require specific corrosion-resistant materials. A number of industrial processes using process heat from HTGRs could benefit from re-optimization and reduction of process temperature, e.g. by new catalysts. Knowing that industrial processes which can use the heat supplied by HTGR are steadily evolving, in particular for optimising their efficiency and minimising their CO2 emissions, interactions in this field with the R&D performed on these processes is desirable.

Following first successful deployments, it is likely that new fuel production capacity will need to be built. This fuel will require high-performance low-cost quality control for manufacturing. Therefore, it is crucial to maintain related test facilities and know-how for irradiation testing and post-irradiation examinations. Other longer term topics include alternative fuel cycles (closed Th-U, symbiotic U-Pu) or the development of the Very High Temperature version of this reactor type with coolant outlet temperatures above 850°C for maximized efficiency and versatility. This calls for development and qualification of new types of structural and functional materials, in particular refractory metals and ceramic composites for which Codes and Standards need to be prepared.

Techniques to minimize waste volumes need to be perfected, such as the decontamination and recycling of irradiated graphite (in synergy with existing waste management programs), or the separation or recycling of TRISO particles from their matrix graphite.

MSR (thermal or fast spectrum) technology topics

The following R&D topics related to molten salt fuelled (both uranium and thorium) MSRs have been identified by GIF (2018) and EC (2019):

- Physical and chemical characterization of (fuelled) molten salt compositions;
- Liquid fuel behaviour analysis and development;
- Qualification of structural materials;
- Instrumentation and control for liquid salt systems;
- Pre-normative research recommendations for component design rule modifications in support to prototypes for MSR;
- Development of on-site fuel processing concepts;
- Development of out-of-pile and in-pile mock-ups;
- Development of a molten salt fuelled MSR demonstrator.

3.4 SMR

3.4.1 Objectives and Motivation

As mentioned in the IAEA (2018) booklet, there is an increasing interest in small modular reactors (SMRs) and their applications. SMRs are defined as power reactors up to 300 MWe (although it should be noted that in the UK, currently a 400-450 MWe SMR is considered), whose components and systems can be shop-fabricated and transported as modules to their designated sites for installation as demand arises. The most promising SMR designs adopt inherent safety features and are deployable either as a single or multi-module plant.

> **The key driving forces of SMR development are fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil power plants, providing the opportunity of cogeneration, supplying energy to remote areas or developing countries with small electricity grids, and enabling hybrid nuclear/renewables energy systems (IAEA, 2018).**

The small size offers potential advantages when compared to large NPPs, in terms of design simplification and potential to use passive systems, increased resilience against external hazards and terroristic acts as well as potential to reduce emergency preparedness zones. Through modularization, SMRs aim for economics of serial production and shorter construction time; this, along with the reduced capital investment per unit and the generation of revenues from initial units while constructing the follow-up ones, is also a key enabler for a significant decrease of the investment risk.

Many different countries (Russia, USA, China, France, India, and, notably, EU) have governmental strategies supporting the development of SMRs (many are integral PWRs, but also HTRs, LFRs, GFRs, MSRs) with projects led by both research centers and industries. The UK government is supporting SMR development through the UK industrial strategy challenge funding, targeting for deployment in the early 2030s.

In the European context, one main potential application of SMRs is represented by installations having power in the order of 100 MWe for the compensation of renewables, due to the policies supporting the increase of share and priority of dispatch of this intermittent energy source. However, the consequent reduced capacity factor would have a detrimental impact on the return of investment making SMRs even less attractive, unless the loss in competitiveness is compensated by national policies. To face such situation, also low-cost thermal energy storage solutions coupled with small-size nuclear energy systems are under consideration and would represent an invaluable asset for the integration with intermittent renewable energy sources, without compromising the financial viability of nuclear power plants in a regulated energy market.

On the other hand, multi-unit sites with a total power in the range 350-700 MWe will represent an option for the replacement of fossil fuel power plants and the supply of process heat to industrial clusters as well as cogeneration of heat for residential areas. In this case, SMRs should be demonstrated to match the temperature needs of the specific industrial application and be safely cosited close to the end-user. It has finally to be noted that. when considering co-generation application, an additional set of challenges emerges from the coupling to industrial (e.g. chemical) installations:

- ✓ Decoupling of accidents and accident initiators in nuclear and industrial parts;
- ✓ Following variable power demand of industrial installation or coupling through heat storage.

The implication of the specific coupling mode and consequences on both nuclear and industrial plants should be obviously carefully analysed in close cooperation with regulators and potential users.

New standards need to be developed and integrated in the existing licensing and certification regimes (ENCO, 2017), with more chances for knowledge sharing and implementation of lessons learned. Although initiatives are ongoing worldwide, licensing regimes in place for the last few decades represent a barrier to meet the ideal goal of internationally harmonized standards. The EU has the opportunity to develop a legal framework for SMRs (if not for all of Europe, at least for member states embarking on a new nuclear power generation capability), compatible with standardized designs and international certification. The long-term advantage will be the possibility to deploy an internationally certified module in any country adhering to the certification program. EU's commercial prospects in deploying a certified technology will improve the competitiveness of the local nuclear supply chain. Modular construction of factory built Systems Structures and Components (SSCs) for a standardized SMR designs will centralize the return of experience, with a progressive improvement in quality. Moreover, the associated costs and time schedules will be constantly optimized, for an on-budget and faster delivery.

Finally, from an economic point of view, some not-easily-measurable advantages of smaller NPPs could give the SMRs a competitive advantage. Complexity linked to the large size might be a reason behind recent failures to deliver large-NPPs on-schedule and on-budget. SMRs are expected to be easier to manage from the EPC point of view, thus improving the "actual" performance of smaller units, as far as a size reduction might increase the number of equipment suppliers, as far as modularization should enable the parallelization of fabrication and installation activities, as far as higher factory fabrication options might reduce the chance of non-compliance with the quality standards.

3.4.2 State-of-the-art and Challenges

LWR

Among the 50 SMRs designs reviewed by IAEA, the short-term deployable SMRs are relying upon the most mature technology: water-cooled reactors. Around the world, various companies offer specific water-cooled SMR designs. Far to be an exhaustive list of designs, the followings can be cited as examples for the LWR technology:

- Russian KLT-40S reactors are installed on a barge, have been transported to their destination, and connected to the grid;
- In Argentina, a prototype CAREM reactor is under construction;
- NuScale is in the middle of the licensing process in the USA;
- Discussion is ongoing in Saudi Arabia for the construction of South Korean SMART design;
- The French industry have formed a consortium to promote their own innovative water-cooled Nuward SMR design (see schematic view).

NUWARD SMR design

Among the different concepts, the so-called integrated designs, in which steam generators and pressurizer are located inside the pressure vessel, are the most promising ones. They indeed offer simpler design and inherent safety advantages. Furthermore, these designs rely on passive systems for residual heat removal during hypothetical loss of coolant accidents or station black out scenarios.

Advanced Modular Reactors

HTGR

High Temperature Gas-cooled Reactors (HTGR for short) are SMR candidates closest to deployment after LWR. They have two important advantages for specific applications:

- An inherent safety feature based on silicon carbide coated fuel particles makes possible to install them in proximity of industrial installations and residential areas;
- High outlet temperature (over 500°C, up to or even exceeding 1000°C) makes them especially useful for industrial heat applications.

In contrast to electricity, heat cannot be transported over long distances. Therefore, reactors providing heat must be located in proximity of user facilities and their power should match the user demand. An optimal size for European market is around 200 MWth. In order to compete economically with larger reactors, one has to find a way to break the economy of the scale. This could be achieved by economy of numbers if HTGRs are produced in a repetitive way in a factory, and by supplying heat for industry in addition to (baseload) electricity. This requirement and the relatively small power bring HTGRs to the SMR class.

Currently, three basic kinds of applications are considered.

Electricity (and possibly heat) production for remote sites. "Micro-reactors" of 10-50 MWth are being considered for such applications e.g. in Canada, to power remote mines. Military bases are another possible application.

Processing heat for industry. Reactors up to 200 MWth producing steam of 550°C could be an exact replacement of coal- and gas- fired boilers commonly used today. They could be installed without any changes in industrial installations, as they usually have their own steam distribution networks. Reactors with higher temperature output are especially suitable for chemical processes like hydrogen or synthetic fuel production.

Cogeneration of electricity and heat for residential areas. Typical cogeneration power plants today are based on coal- or gas-fired boilers producing 550°C steam. The steam drives turbines producing electricity and the "waste heat" in form of ~200°C steam is used to feed district heating networks. Reactors of 100-300 MWth producing steam of 550°C could be again a good replacement for such power plants.

LMFR

Main challenges to (advanced) SMR deployment in Europe are the lack of SMR consensus, the decrease of gas prices, the "nuclear fear" and lack of "nuclear vocation", the dense European electric grid and the lack of a licensing framework specifically applicable to advanced SMR technologies. Improved safety, sustainability, proliferation resistance and economics of Generation4 fast reactors are considered key factors to mitigate the identified societal, economic and environmental threats, thereby opening new perspectives for Small Modular Fast Reactors (SMFR).

More than twenty years of experimental activities on heavy liquid metal coolants have significantly increased the knowledge and experience on this subject across the EU. The large databases of physical, chemical, thermal-hydraulic properties of lead coolant have allowed designers to develop technical solutions that simplify the plant design, thus reducing capital cost, while simultaneously achieving a very high level of safety progressively closer to the elimination of outside containment consequences. Thanks to such constant advancements, the LFR technology has now actual perspectives for a short-term deployment of SMFRs implementing the so-called closed fuel cycle, allowing not only a full use of the uranium resource (sustainability) but also contributing to a strong decrease of the production of high-level waste and hence to the size reduction and needs of the geological repository.

> ***Improved safety, sustainability, proliferation resistance and economics of Generation4 fast reactors are considered key factors to mitigate the identified societal, economic and environmental threats, thereby opening new perspectives for Small Modular Fast Reactors (SMFR).***

In favour of this choice there are many aspects inherent to the LFR technology such as the high boiling point, exceeding 1700°C, primary system operating in atmospheric conditions, the extensive use in the designs of passive safety features as well as the high retention capability of lead with respect to fission products providing an inherent barrier to external radioactivity release, strengthening Defense-in-Depth and supporting reduced emergency preparedness requirements thus facilitating siting near populated or industrial areas.

Lead-cooled SMFRs feature significant export potential in light of their compatibility with small remote electricity networks, intermittent energy sources and, through their higher operating temperature relative to LWRs, cogeneration applications (steam side temperature are presently as high as 450-480°C, but further enhancements can be expected with technology improvements on corrosion compatibility of materials with molten lead).

These features, which supplement the previously mentioned advantages in terms of multi-unit siting and siting in proximity of populated or industrial areas, are cornerstones of the SMR philosophy and result in the LFR being an optimum candidate for global deployment. Moreover, when combined with modular design and construction techniques, plant characteristics such as a high core power density and compact containment as well as reduced releases to environment represent important assets for compensating the small design scaling factor and achieving economic viability. Design and modularization factors around 0.8-0.85, respectively (i.e. 20% and 15% saving factors compared to reference costs for large scale reactors), are necessary for the SMR-LFR to achieve a profitability in line with PWR technology. Profitability is sustained by the shorter deployment time of each SMFR compared to larger plants, anticipating the revenue stream and the pay-back time.

- As already noted in the introductory section, some not-easily-measurable advantages of smaller NPPs could give the SMFR a competitive advantage especially because they are easier to manage from the engineering, procurement and construction point of view. Moreover, the enhanced sustainability in terms of natural resources and the minimization of spent nuclear fuel brought by LFRs, are peculiar features of the technology that shall be factored in, since they could determine potential savings at system level and higher public acceptance, when a broader view is considered;
- Within the SNETP advanced reactors initiatives, both the MYRRHA and ALFRED developers are seriously considering an industrial deployment in terms of SMFRs, as a natural and short time frame possibility to implement the technology advancements already achieved. Due to the lack of operational experience in western countries, the commercial deployment of the SMFR technology shall be previously supported by the construction and operation of a demonstrator.

MSR

With respect to small modular versions of MSRs, the challenges are similar to the challenges mentioned for MSRs in general.

3.4.3 R&D Topics

LWR

The dynamic development of integrated light water (LW)-SMRs requires R&D regarding:

01

The core:

Use of burnable poisons specifically in the case of soluble-boron-free designs. The challenge is to smooth the local power distribution while moving from a homogeneously distributed neutron absorber configuration to a heterogeneous neutron absorber distribution.

02

The vessel and its internal parts:

Development of compact heat exchangers and associated fabrication processes. The design of these compact heat exchangers will fulfil different conditions, their ability to exchange heat from primary to secondary circuits and their capability to remove the reactor residual heat under natural convection conditions.

03

The use of passive safety systems to cope with different accident scenarios:

Understanding the heat transfer in natural circulation mode and ensuring the function of safety features relying on natural circulation are of primary importance. In order to reduce uncertainties, thermal-hydraulics codes and associated correlations need to be improved, in particular in the field of boiling and condensation at intermediate or low pressures. In specific cases, additional experiments are required.

04

The management of hypothetical severe accident:

SMRs offer potential advantages like significantly reduced emergency planning zones in case of a severe accident. In order to demonstrate such capacity, special attention will be paid on the in-vessel core retention strategy with the associated improvement of core degradation and corium progression codes.

05

The reduction of on-site construction time:

This goal is achieved thanks to a large use of modular construction techniques.

06

Human Factors:

In most cases, SMRs designers propose multi-module SMR plants monitored via a single control room. Such an option raises issues of control room staffing and human factors.

07

Probabilistic Safety Analysis:

The development of methodologies regarding safety probabilistic safety analysis in order to take into account the reliability evaluation of passive systems, the dynamic aspect over long periods, the monitoring of several units per site with shared systems and operators.

08

Licensing:

The market addressed by LW-SMRs is clearly worldwide including currently non-nuclear countries. To foster the development of such market of SMRs at large scale, the development of a common methodology for safety analysis of water-cooled SMRs and/or European or internationally accepted generic design assessment scheme is a key advantage.

Advanced Modular Reactors

The technology of advanced modular reactors is either, well proven and does not require any generic R&D, or it requires similar R&D as larger scale alternatives mentioned already in the previous chapter. Specific research and development is, however, needed for some SMR applications. Basic challenges are related to "mass production" of the reactors:

- Simplification of the design
    - Benefits from small power and never-melting fuel;
    - Simplified shutdown systems;
    - Containment vs confinement, simplified reactor building, etc.
- Compactness of the design
- Making design suitable for manufacturing
- Using commodity components

As already noted, another set of challenges emerges from coupling to industrial (e.g. chemical) installations:

- Decoupling of accidents and accident initiators in nuclear and industrial parts
    - Ensuring that nothing in industrial part can influence operation of the nuclear part and vice versa
- Following variable power demand of industrial installation
    - Load following mode;
    - Heat storage (to enable the reactor to run full power all the time);
    - Varying the ratio of produced heat and electricity.

Such research should be done in close cooperation with regulators and potential users.

4. ENABLING CONDITIONS

4.1 Safety of Nuclear Power Plants

4.1.1 Objectives and Motivation

The safety of nuclear installations was an absolute priority from the very beginning of nuclear reactor construction in 1940's. During the nearly 80 years of design, construction and operation of research reactors and commercial nuclear power plants, the concept of nuclear safety has developed into a complex and sophisticated system, where the very core is the defence-in-depth approach. Nuclear safety is a critical condition for sustainable NPPs operation and therefore SNETP puts emphasis on R&D activities focused on increasing safety of NPPs and improving understanding of accident phenomenology and abilities for NPP safety and risk assessment. An accident in any country in any part of the world effects the nuclear sector globally. That's why support of international nuclear safety programs and harmonization of approaches to nuclear safety is another important aspect of nuclear safety effort.

> *Nuclear safety is a critical condition for sustainable NPPs operation and therefore SNETP puts emphasis on R&D activities focused on increasing safety of NPPs and improving understanding of accident phenomenology and abilities for NPP safety and risk assessment.*

With appropriate site risk evaluations, plant designs and management, the Gen II and Gen III NPPs show high levels of robustness and low probabilities for severe accidents. The deployment of advanced Light Water Reactors (LWR) for electricity production could valuably make the bridge between the ageing nuclear installations currently in operation, the Generation III reactors now under construction, and the Generation IV reactors, proposed by the Generation IV International Forum (GIF). But, despite the highly efficient accident prevention measures, some accident scenarios may, with a low probability, result in a severe accident, as emphasized by the events in Fukushima. A nuclear severe accident can result in core melting, plant damage and dispersal of radioactive materials outside of the plant containment, thus threatening public health and the environment. For innovative reactor concepts of non-LWR type, the application of the LWR severe accident methodology cannot be simply transposed from the LWR technology due to different phenomena that play a role and due to different engineering features. For all reactor types, inherent and passive safety should be continuously assessed and enhanced.

The deterministic safety assessment of NPP is being extended in several directions, mainly to design extension condition area (based on previous works of the European Utility Requirements organization and WENRA). More systematic assessment of vulnerabilities to defence-in-depth is another important field of application of modern deterministic tools and methods. Probabilistic analysis was also strongly influenced by the events in Fukushima and work in areas like external hazards (including extreme events), multi-unit PSA, human factor, fragility analysis has been initiated or strongly extended.

In the area of severe accident mitigation and assessment, the main six objectives are as follows: in-vessel corium/debris coolability, ex-vessel corium/debris interactions and coolability, mitigation of gas explosion risk in containment, source term assessment and mitigation, severe accidents linkage to environmental impact and emergency situations, management of severe accident scenarios, etc.

4

4.1.2 State-of-the-art and Challenges

One of the most important parts of nuclear safety is the NPP safety and risk assessment. It serves not only in phase of licensing of a new plant, where the safety analyses are the very core of the preliminary Safety Analysis Report (SAR). The deterministic and probabilistic analyses are widely used in the phase of NPP design, licensing, start-up, support of operation, periodic safety assessment, validation of accident management guidelines, and support of NPP modifications. The tools and methods utilized in NPP safety assessment have experienced dynamic development in last decades. The original approach with deterministic analyses of a spectrum of transients and accidents up to maximal design basis accident (DBA) performed with conservative computer code and documented in the SAR has been gradually extended by probabilistic risk assessment, application of best-estimate computer codes, severe accident analyses, human reliability analysis, assessment of external hazards, quantification of uncertainties of safety analyses, analyses of design extension conditions, etc.

The extension of plant safety and risk assessment is accompanied by progress and development of computational tools which are utilized for safety and risk assessment. Advanced computer codes utilized for DBA analyses are continuously being developed. Shift from 1-dimensional hydraulic models and point kinetics to 3-D modelling of the reactor core and the cooling systems, coupling of system thermal-hydraulic codes with core physics (multi-physics coupling) and/or computational fluid dynamics codes (multi-scale coupling) are the tasks being solved at present. A special type of multi-physics computational tools are the fluid-structure interaction (FSI) computer codes that are very promising in areas like reactor internals loads, fuel bundles vibrations, heat exchanger behavior in accidental conditions, water hammer simulation, etc.

Methods and programs utilized for probabilistic risk assessment have developed to complex computational tools enabling quantification of plant risks in both nominal and shutdown conditions including human reliability analysis, external hazards, and grid impact. Combining of deterministic and probabilistic methods is also a very promising direction of plant safety assessment. However, as always simulation tool development and experiments to provide data for development and validation need to go hand in hand. The ever-increasing computational capabilities put a challenge to the usage of more sophisticated measurement techniques. Moreover, the instrumentation and control systems of NPPs could represent a challenge both in term of safety application and during the licensing process.

Considerable knowledge has been gained about severe accident phenomenology for LWRs through research carried out over the last 40 years, for instance in the international project Phébus FP on in-pile experiments, and in the SARNET Euratom projects from 2004 to 2013. More recently, many international R&D projects have started in diverse frameworks such as Euratom collaborative projects and OECD/NEA. One can underline the importance of projects launched in the latter framework and led by Japanese organizations about the interpretation of the accidents in Fukushima. For the advanced reactors, and in particular, for the sodium-cooled technology, severe accident phenomenology has been defined in the past and has been further studied during the ASTRID-project. For lead-technology, the severe accident phenomenology leads to a significant different concept and needs specific development. The same is true for high temperature and molten salt reactor technology which like lead-cooled reactors relies on different principles.

For each of the six main objectives defined for severe accident analysis, challenges have been identified:

With respect to in-vessel corium/debris coolability, the objective is to reduce the remaining uncertainties on the possibility of cooling the reactor core structures and materials during a severe accident, either in the core region or in the vessel lower head. This should limit the progression of the accident. Substantial knowledge exists concerning cooling of intact rod-like core geometry. Significant progress occurred in the recent years about the core degradation late-phase, in particular on the behaviour of corium and debris in the vessel lower head. This is currently being completed.

With respect to ex-vessel corium/debris interactions and coolability, the major safety challenge after vessel lower head failure is to preserve containment integrity against rapid failure (e.g. due to steam explosion) or slower failure by basemat melt-through (Molten-Core-Concrete-Interaction (MCCI)) and/or containment over-pressurization. Significant new knowledge was obtained in the past years on the premixing phase of steam explosion and on MCCI phenomena but main remaining issues have recently been synthetized in OECD/NEA reports.

With respect to the mitigation of gas explosion risk in containment, significant knowledge was gained in the past years on containment gas distribution and on the efficiency of passive autocatalytic recombiners during severe accidents.

The source term to the environment refers to the amount, chemical speciation and isotopic speciation of all radio-elements that can be released to the environment. A significant progress to this respect came from recent R&D international projects in European and OECD/NEA framework but some knowledge gaps remain to be addressed.

In addition to NPP safety concern, severe accident R&D activities target the improvement of emergency preparedness and response and of the prediction of the environmental impact. Associated needs will have to be discussed in the frame of the memorandum of understanding signed in 2017 between NUGENIA and the radioprotection European platforms. Fast-running tools are necessary in the emergency preparedness phase and in the response phase. Improving on-site atmospheric transport and dispersion models of radionuclides will allow a better interface between the in-reactor source term evaluation tools and the atmospheric transport and dispersion tools that mostly consider mid-to-far fields.

With respect to the management of severe accident scenarios, integral codes (or system codes) are essential for simulating severe accident scenarios including the evaluation of the source term into the environment, as well as the evaluation of severe accident management measures and the efficiency of mitigation systems. In addition, the accidents in Fukushima have underlined the importance of the behaviour of spent-fuel pools in case of loss of cooling. And finally, the consolidation of shared databases for methods and tools for severe accident management guideline assessment and improvement will be necessary in the future.

4.1.3 R&D Topics

The advanced methods and tools for plant safety and risk assessment enable upgrading of reactor safety systems to handle new safety demands, effective replacement of obsolete components, power uprates, improvement of economic parameters of NPP operation, support of LTO, etc.

Major challenges and related R&D topics in the area of plant safety and risk assessment are as follows:

- **New approaches to safety assessment:**
    * Methodologies extending the scope of existing probabilistic safety assessment (external events, cascading/conjunct events characterization, fragility / operability / technical resilience analyses, human organizational factors and risks, etc.);
    * Long-term and multi-unit loss of safety functions from internal or external event or combinations of both conceivable at the plant site, including station black out, loss of the ultimate heat sink or both;

  - Development and validation of advanced tools and methods for deterministic safety analysis multi-scale and multi-physics capabilities;
  - Integrated deterministic-probabilistic safety assessment;
  - Simulation tools for fire modelling;
  - Methodology of safety assessment of design extension conditions (DEC) and performance of diverse and alternative means and measures;
  - Further progress in quantification of uncertainties of safety analyses. Application of uncertainty methods to further areas (neutron cross sections and 3D neutron-kinetic calculations of transients, pressurized thermal shock, sub-channel calculations, etc.);
  - Support to continuous operation of remaining European experimental facilities with emphasis on design extension conditions accidents and shutdown conditions (essential condition for computer codes development and validation).
- **Development of safety requirements, criteria and rules for passive systems:**
  - Credibility of passive systems activation and load-up to required capacity;
  - Safety and reliability assessment of the capability of passive safety system to perform the assigned function;
  - Dependence on external energy sources for initialization and execution of the assigned function;
  - Assessment of different phenomena that could lead to the loss of assigned function;
  - Uncertainties and safety margins associated with passive systems;
  - Methodology for the reliability evaluation of passive systems and its integration into probabilistic safety assessments;
  - Extension of computer codes validation for passive systems modelling (specific challenges).
- **Development of more sophisticated instrumentation and control systems for safety applications:**
  - Implementation and safety assessment of electronic and programmable devices as more use of such devices in NPPs can be expected in the near future;
  - Methodology for the reliability evaluation of digital instrumentation and control systems and its integration into probabilistic safety assessment;
  - Implementation and safety assessment of wireless technologies for data transmission.

With respect to the six main objectives defined for severe accident analysis, the following R&D topics are identified:

- **In-vessel corium/debris coolability**
  - Coolability of a degraded core/corium with particulate debris during reflooding by water injection;
  - Transient corium/debris behaviour in the vessel lower head;
  - Integrity of an ablated vessel lower head with external cooling.
- **Ex-vessel corium/debris interactions and coolability**
  - Debris formation during melt relocation to the ex-vessel cavity;
  - Corium/debris coolability by top flooding during MCCI, in particular for metal-rich melts;
  - Consequences of ex-vessel steam explosion, in particular for stratified configurations with corium spreading under water;
  - Long-term cooling of corium/debris, including efficiency of the coolant recirculation systems.
- **Mitigation of gas explosion risk in containment**
  - Containment atmosphere gas combustion, with deflagration to detonation transition, and corresponding modelling improvements, in particular for extrapolation (e.g. scaling) to actual NPP geometry;
  - Evolution of containment leakages due to severe accident conditions up to the long term.
- **Source term assessment and mitigation**
  - Improvement of predictability of iodine and ruthenium chemical behaviour in reactor cooling system and containment, in particular all remobilization and re-vaporization phenomena for delayed source term linked with severe accident long-term management.

- **Severe accidents linkage to environmental impact and emergency situations**
  - * Improvement of in-reactor liquid source term and associated releases paths;
  - * More accurate atmospheric transport and dispersion models, in particular near–field models and impact of physical and chemical transformation of radionuclides;
  - * Improvement of severe accident management evaluation tools for accident progression, including mitigation actions, and consequences (e.g. effect of different severe accident venting strategies);
  - * Improvement of fast-running tools, including instrumentation and information transmission, either based on severe accident evaluation codes or validated by comparison with these codes.
- **Management of severe accident scenarios:**
  - * Continuous capitalization of knowledge in the integral codes and of their capabilities to support improvements of severe accident management guidelines;
  - * Extension of the current crosswalk exercises among the major severe accident integral codes;
  - * Development and qualification of specific instrumentation for supporting the management of all severe accident phases, including long term;
  - * Accidents in spent-fuel pools (thermal-hydraulics, fuel cladding oxidation, criticality risk, accident and source term mitigation), and improvements of applicability of the integral codes.

Note that for non-LWR's, the safety approach used for LWR's cannot be adopted straightforwardly. An interactive process with the safety authorities is necessary in order to agree on a safety approach and underlying guidelines and rules that take into account the specific characteristics of innovative reactor concepts and coolants.

4.2 Fuel Development, the Fuel Cycle, and Spent-fuel Management

4.2.1 Objectives and Motivation

For the LWR-fleet of NPP's, the currently adopted fuel cycle is the open fuel cycle with final direct disposal in geological repositories or mono-recycling of plutonium via the production of MOX fuel loaded in LWR reactors. For these LWR's, fuel development and spent-fuel management research and innovation topics cover the development of nuclear fuel for existing, advanced and innovative core designs including

- ✓ assembly and control rod design and manufacturing improvements with a focus on robustness and economics;
- ✓ focus on safety through Accident Tolerant Fuel development;
- ✓ safety justification;
- ✓ security of supply and Europe independency;
- ✓ within assembly instrumentation;
- ✓ manufacturing;
- ✓ transport;
- ✓ use within reactors (nuclear fuel behavior mechanisms including post-irradiation examination);
- ✓ pre-disposal management of spent fuel (which may include wet storage, transport, drying, dry storage and repacking);
- ✓ reprocessing;
- ✓ the production of recycled fuel from the products of reprocessing.

This includes the safety issues linked with fuel behaviour in normal operation, transient and accident conditions in addition to the safety of the fuel cycle including criticality prevention, heat management and containment. Of particular importance is that the lessons from the accident in Fukushima are taken into account to propose research, development and innovation to improve the safety and resilience of the existing and new build LWR reactor fleet.

Nuclear fuel production and use in commercial reactors have reached a relatively mature state. Nevertheless, there is motivation to improve existing fuel designs and manufacturing and to develop innovative fuel to further improve reliability and safety, together with flexibility of operations. The security of supply is also a key stake for Europe to ensure the sustainability of nuclear power supply. Research on fuel behavior mechanisms and computational codes research is focused on behavior in both normal operation and accident conditions, performed experimentally and with simulation models (computer codes). An understanding of fuel behavior is underpinned by fuel R&D, which must address new safety requirements and design innovations such as Accident Tolerant Fuel or Advanced Technology Fuel (ATF) and advanced recycled fuels, high burn-up, high linear power, SMR fuels, long refuelling intervals, and flexible operation. It must also address differences in behaviour engendered by more incremental changes of the fuel pellets, cladding and assembly structural components.

The improved understanding of fuel rod behaviour mechanisms is enabled by experimental observation, measurements complemented by physical models, and facilitated by modelling using physics-based simulation tools. This improved understanding and the results of physical modelling can be used to improve fuel performance codes, as is pursued within the fuel sub-programs of the EERA-JPNM as outlined by EERA-JPNM (2019), with which SNETP signed a memorandum of understanding to ensure collaboration. Fuel performance codes are essential for fuel design and licensing. A fuel performance code calculates the evolution of the thermo-mechanical and thermo-chemical state of a fuel rod during its irradiation (and potentially also during any post-irradiation storage) as well as, potentially, the fission gas and fission product behaviour.

Fuel treatment, transportation and interim storage (spent-fuel management) research satisfies the need to fully understand the challenges faced by managing the extended storage periods of the spent (used) fuel and their storage systems following reactor utilization. Management activities include handling of the spent fuel, associated diagnostics (determination of fuel assembly and storage system condition), storage in spent-fuel pools at power plants, transport, interim storage in either wet or dry conditions before either reprocessing and recycling or transfer for final disposal, all need to be qualified and validated. Recycling of UO2 and metallic fuels is well established within some countries in the EU. The continued development of fuel and the effects of higher burn-up irradiations raise the potential for changes in recycling process parameters.

Although with open fuel cycles or partially closed fuel cycles based on mono-recycling of plutonium the sustainability in terms of resource utilization and high-level waste minimization can be gradually increased as mentioned above, major progress can only made through closed fuel cycles with fast reactors. Fast nuclear reactors can be designed to reach conversion ratios equal to or even greater than one, in such a way that no more natural fissile isotope is needed to sustain nuclear energy production since the reactors generate more fissile isotopes than they consume to produce energy. These reactors, also called "breeders", need to be fed only with fertile isotopes (^{238}U or even ^{232}Th) which are available in plentiful amounts, both in nature and as leftovers from the present enrichment of the nuclear fuel in ^{235}U.

To optimize high level waste management, two generic fuel cycle scenarios exist:

- A fleet of fast neutron critical reactors that simultaneously produce electricity and transmute all the actinides. The only input into the system (reactors and fuel cycle facilities) is natural or depleted uranium and the output is electricity and residual intermediate level waste (ILW) plus high level waste, including the fission fragments, activation products and actinide reprocessing losses. In this option, the minor actinides (MA) could be homogeneously diluted within the fuel or separated in the form of dedicated targets. However, the core design of these reactors has to be optimised from the point of view of neutron economy and safety performance, and the feasibility of the associated fuel cycles should also be addressed;
- A "double strata" reactor fleet. The first stratum is a set of critical reactors dedicated to electricity production using "clean fuel" containing only uranium and plutonium. The reactors in this stratum can be either current or future thermal reactors or fast reactors. Some European countries may want to consider long-term plutonium multi-recycling R&D both in fast spectrum reactors and in thermal spectrum ones in the first stratum. The second stratum is devoted to transuranic elements or minor actinide transmutation and is based on special fast reactors or subcritical fast systems, Accelerator Driven Systems (ADS), loaded with homogeneous fuels with high minor actinide content.

The evaluation of this type of scenario indicates that while maintaining the safety of operation, they should ultimately be able to significantly reduce the long-term uranium consumption, making the present reserves last for several thousand years. At the same time, the high-level waste long-term radiotoxic inventory could be reduced by more than a factor of 100 and its heat load by more than a factor of 10, at medium and long term. According to these studies the last figure will allow the deep geological repository capacity to be increased by factors from 3 to more than 10 (in hard rock, clay and tuff geological formations).

4.2.2 State-of-the-art and Challenges

The main nuclear fuel suppliers in Europe are currently Framatome, Westinghouse, ENUSA, GNF and TVEL. The existing theoretical and experimental knowledge base consists of the vendors' own R&D, the operational experience of utilities, research entities such as national laboratories, technical service providers, universities and international organisations, in particular the IAEA, OECD/NEA and WNA. Experimental facilities including research reactors, hot cells and hot laboratories need to be available for research and testing, supported by extensive modelling and simulation capability using state of the art computer codes.

Uranium dioxide (UO_2) enriched up to 5% in the form of solid or annular pellets in zirconium alloy cladding remains the most widely used fuel in European reactors, primarily LWRs. MOX (mixed uranium-plutonium oxide) fuel also is used in limited quantities, mainly in France, where large scale reprocessing and manufacturing facilities are available. For LWR fuel assemblies, the main construction materials are again zirconium alloys, with nickel alloys and stainless steels also used for some assembly components. Control rods are currently manufactured primarily from either silver-indium-cadmium (Ag-In-Cd) alloys or contain boron carbide (B_4C).

The properties of all these materials and fuel assembly design are relatively well established. However, the drive for continuous improvement in safety, reliability and performance through improved understanding and evolutionary adjustments necessitates further studies and ongoing development. Fuel performance and reactor physics codes have been developed over many years and validated using data from operation and dedicated experimental programs. These are routinely used for simulation of normal operation, transient conditions and accident scenarios. Nevertheless, enhancements in simulation methods, enabled by ever improving computing capabilities, are continually sought as there is a desire for better mechanistic understanding of fuel behaviour in-reactor. This endeavour, with a projection towards fuels for advanced reactors by centering on MOX and MA-bearing fuels, is especially the focus of the fuel activities within EERA-JPNM.

> ***The drive for continuous improvement in safety, reliability and performance through improved understanding and evolutionary adjustments necessitates further studies and ongoing development.***

Spent-fuel management of the various nuclear fuel types from both commercial and research reactors is a mature practice benefiting from the accumulated knowledge and experience acquired over more than fifty years. Nevertheless, there is room for improvements in safety, security (proliferation resistance), economics and environmental aspects. Spent-fuel management is carefully regulated by national regulators, usually reflecting recommendations of international organizations, in particular Euratom and the IAEA. Within the EU, a range of spent-fuel storage arrangements are employed, in some countries fuel is stored primarily at the reactor site where it was irradiated, whereas in other countries, centralized facilities exist for interim/long-term storage following an initial cooling period at the reactor site.

The reprocessing of UO2 and metallic fuels has been well established within some parts of the EU. However, there is the potential for the extension of existing reprocessing techniques to more challenging fuels, such as high burn-up fuels and multiple recycled MOX, as well as development of advanced reprocessing techniques such as pyro-processing. In addition, the reprocessing of potential novel LWR fuel compounds such as those proposed for ATF, needs to be considered in particular by linking with Gen IV programs where there is currently greater experience of some of the proposed materials. In addition, there are many exotic fuel forms which been produced in Europe as a result of past development programs including Gen IV pre-cursors which are difficult to reprocess but may not be suitable for direct disposal in a geological repository.

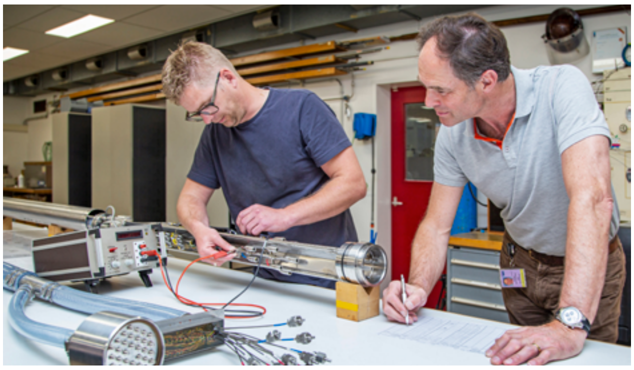
The deployment of advanced fuel cycles involves large technological challenges:

- synthesis of new fuels (targets) and fuel assembly designs bearing significant amounts of MA, and their fabrication technology (this is a major focus of the research on nuclear fuel performed within the EERA-JPNM);

- the technologies of fast neutron reactors and ADS, including new materials, thermal-hydraulics, simulation tools, nuclear data and, in the case of ADS, the coupling of an accelerator with a subcritical core;
- new recycling technologies based on advanced aqueous and pyro-metallurgic reprocessing, adapted to highly active and hot fuels containing large amounts of plutonium and minor actinides, and minimizing the production of secondary wastes.

For most of these topics, significant lab demonstration exists, but now the step towards larger scale demonstration needs to set.

Additional fuel cycle scenarios studies are required to complete the evaluation on the feasibility of sustainable solutions for the transition period from the present nuclear fleet until the deployment of fast nuclear systems, taking into account present perspectives for deployments of advanced thermal reactors and future fast neutron reactors. Similarly, the evaluation of the impact of these technologies in the deep geological repository designs, taking into account updated nuclear policies of EU Member States, technology deployment and different options for the fast systems deployments, needs still to be completed.



Assembly workshop for irradiation rigs at NRG
Photo: NRG (2019)

4.2.3 R&D Topics

The following R&D topics are identified, some of which overlap with activities on fuel coordinated within the EERA-JPNM:

- Increasing the safety margins of nuclear fuels and improving behavior under operation and accident conditions including the development of new ATF forms;
- Improved economics of nuclear fuels in particular through allowing high burn-ups, increased enrichment (beyond 5%), and potential new high density fuel forms;
- New control rod design for higher flexibiliy;
- Increased nuclear fuel recycling through the use of reprocessed uranium and improved MOX fuels including multiple recycled MOX, high plutonium content and minor actinide bearing MOX;
- Improvements in assembly design and optimization including attempted elimination of grid-to-rod fretting and the prevention or mitigation of damage by foreign objects;
- Development of new fuel designs, manufacturing capabilities and transport solutions for ensuring a sustainable security of supply and independency of Europe supply chain;
- Improvement of fuel performance and safety computer codes and their validation by quantifying and reducing uncertainties and extending qualified experimental data;
- Introduction and validation of more mechanistic and multi-scale modelling packages for the assessment of both existing and innovative fuel designs;
- Improvement of post-irradiation examination (PIE) methods;
- Ensuring availability of key experimental facilities (research reactors, hot cells and hot laboratories, mechanical and thermal-hydraulic test facilities) and expanding their capabilities to meet future requirements;
- Handling and storage of leaking fuel assemblies (spent-fuel pool and interim wet and dry storage);
- Understanding the evolution of spent-fuel and storage systems over multi decade or even longer temporary storage and development of effective means for monitoring compliance under nominal and off-nominal conditions;
- Optimization of storage systems to minimize handling of fuel and casks after longer term storage, including the interface to deep geological repository;
- Spent-fuel heat generation and burn-up credit challenges (code validation, uncertainty reduction and licensing issues);
- The reprocessing and recycling of challenging fuels (e.g. high burn-up, multiple recycled MOX) and advanced fuels (e.g. ATF) as well as advanced reprocessing technologies (e.g. pyro-processing);
- Use of advanced integrated computational

tools for development of integrated waste management strategies;

- new fuels (targets) and fuel assembly designs bearing significant amounts of minor actinides, and their fabrication technology, thus includes plutonium- and minor actinide-bearing fuels including thorium oxide (ThO2) matrix (thorium MOX) and inert matrix fuels for plutonium and minor actinide burning applications;
- new recycling technologies based on advanced aqueous and pyro-metallurgic reprocessing technologies, adapted to highly active and hot fuels containing large amounts of plutonium and minor actinides, and minimizing the production of secondary wastes.

In Summary

The overall objectives with respect to the fuel cycle and spent-fuel management are to improve the operation of NPPs and the nuclear fuel cycle at large in the fields of in-reactor and out-of-reactor nuclear fuel management as to be more:

- Safe
- Sustainable
- Secure (proliferation resistant)
- Environmentally friendly
- Reliable and economic

One key objective is to reduce the time to deployment of innovative new technologies across the whole technical area so as to realize the safety and economic benefits as soon as possible.

4.3 Waste Management & Decommissioning

4.3.1 Objectives and Motivation

Waste management and decommissioning covers the management, treatment and disposal of waste arising from operations across the nuclear fuel cycle (including fuel fabrication, power generation and reprocessing). Beyond waste management, the area incorporates the dismantling and decommissioning of nuclear power plants and fuel cycle processing facilities as a last step in their lifetime. Finally, it also considers waste minimization and recycling of non-fuel materials. The focus is on the identification of best practice from the international community, development and maturation of innovative technology and methods that drive towards improved safety, enhanced environmental performance, sustainable solutions and project efficiencies.

According to IAEA (2019), 178 nuclear reactors have been permanently shut down of which about 10 have been fully decommissioned; many other nuclear facilities have also been decommissioned (such as research reactors, radioisotopes production facilities, reprocessing plants, fuel fabrication facilities, and military reactors). Similarly, nuclear plants have operated successfully for many decades and the arising wastes managed safely, through treatment, storage or disposal. A significant amount of experience and knowledge has been accumulated and it is important that this is shared as the number of waste management and decommissioning operations increases. This body of knowledge will grow further as experience is gained and will define current best practice. This knowledge should also inform the design for future systems. The current challenges are to develop enhanced approaches to minimize waste arising, through design, operation and decommissioning, to enhance waste treatment processes and to develop technologies and approaches to deliver decommissioning safer, cheaper, faster and sustainably.

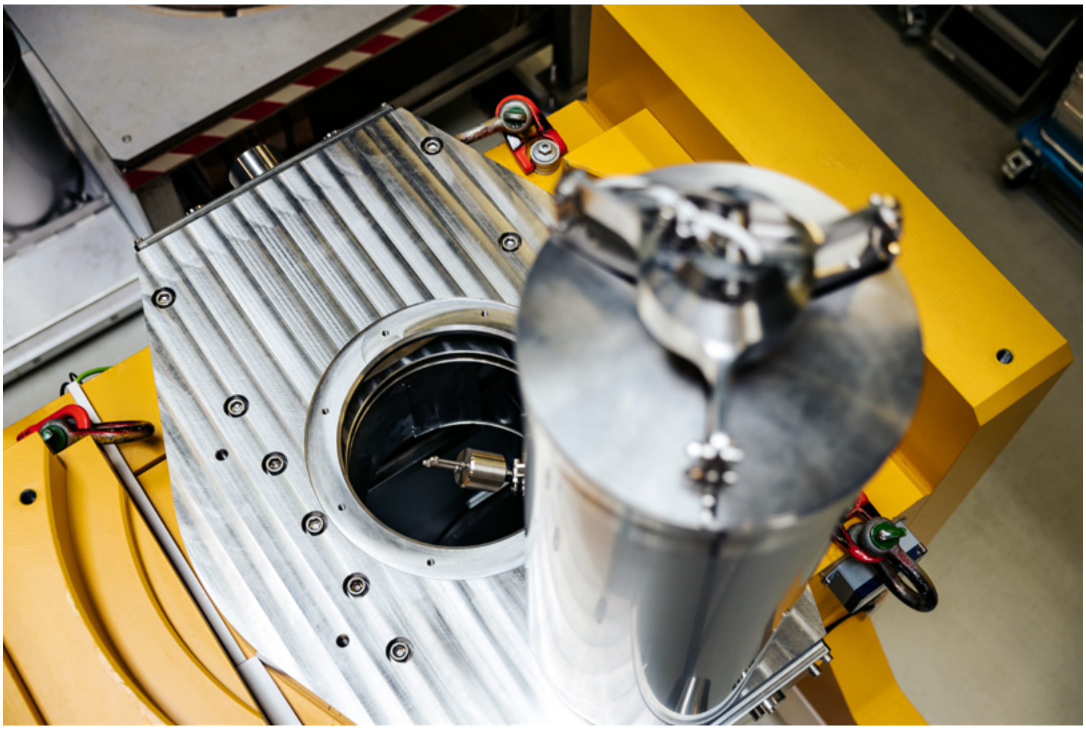
4.3.2 State-of-the-art and Challenges

A number of decontamination, waste treatment and conditioning methods and technologies have been developed over many years. These are used alongside the techniques for waste management of special categories of waste, such as Tc and C-14 waste, Be, irradiated graphite, mixed radioactive and toxic waste. Nevertheless, potential for technology improvements to reduce cost, reduce volumes for disposal and risks are not exhausted. Methods for decontamination and certification for reuse and recycling of various materials (metals, concrete) have been introduced. Experience from decommissioning and dismantling of nuclear facilities is being continuously accumulated allowing for the drafting of guidelines and best practices.

In the waste management area, the focus is on the implementation of the waste hierarchy in the context of radioactive waste. This involves characterization of waste, innovative approaches for treating waste (decontamination and waste revalorization), waste storage, waste form development, long-term condition monitoring and disposability. Innovative approaches can reduce the burden of waste management activities and disposal and lead to a more sustainable long-term approach.

As decommissioning and dismantling activities grow across the globe, significant experience is being gained. For the decommissioning and dismantling area, the focus is on development of pre-planning and programming for decommissioning, decommissioning strategies and the transition phases between operation and decommissioning. Key technical areas that underpin the D&D activities are plant characterization, decontamination techniques, dismantling equipment, remote operations (including robotics) and land remediation. Active demonstration of new technology is vital to increase the technology readiness and demonstrate the maturity of new approaches.

> ***Experience from decommissioning and dismantling of nuclear facilities is being continuously accumulated allowing for the drafting of guidelines and best practices.***



Container for radioactive waste from experiments
Photo: NRG (2020)

4.3.3 R&D Topics

The following R&D topics are identified:

- Minimization of waste production by design and material selection and operational measures and development of advanced waste treatment and conditioning technologies;
- Development of efficient dismantling technologies for structures and components including remote dismantling techniques;
- Waste minimization strategies for decommissioning including safe release of material to the environment, recycle/reuse,

disposal to very lowlevel waste repositories along with reliable and cost -effective activity measurement techniques;

- Learn from current experience and identify and share best practice in waste management and decommissioning;
- Develop characterization techniques for waste inventory assessment and plant and facility assessment to aid planning for decommissioning;
- Innovate enhanced decontamination and dismantling technologies for structures and components, incl. remote dismantling techniques;
- Establish improved treatment technologies (thermal or other) to reuse/recycle materials, minimize waste volumes and to develop robust and passive waste forms;
- Accelerate the introduction of new technologies and technical approaches through inactive and active demonstrations;
- Waste minimization strategies for decommissioning, including safe release of material to the environment, recycle/reuse, disposal to very low level waste repositories (landfills) along with reliable and cost-effective activity measurement and assay techniques;
- Organizational aspects: Standardization of processes, Identification of synergy effects for multi-unit sites or fleet-wide D&D projects, optimization of post-operational phase;
- Change Management from operation to decommissioning organization.

4.4 Social, Environmental and Economic Aspects for Research, Production and Use of Nuclear Energy

4.4.1 Objectives and Motivation

To ensure sustainability of nuclear energy production and its position at the future energy market, it is important to focus on the following key aspects and conditions:

- **Safe operation and minimum impact on environment**
    * to keep credit of nuclear power as a low-carbon and environment-friendly source of energy
- **Economy and competitiveness**
    * more exact prediction of safety margins, risk informed support of decision making, fuel cycle optimization, LTO
- **Social and political acceptability**
    * make use of existing and new ways of communication, open policy
- **Ability to survive in changing conditions**
    * NPP operation in changing energy-mix and under new grid codes

All these aspects and conditions are mutually interconnected and conditioned, e.g. safe operation and minimum impact on environment is the best argument in promoting nuclear power in social dialogue. There is number of other social, environmental and economic conditions and aspects important for sustainability and development of nuclear energy, like continuous effort in non-proliferation area, progress in nuclear waste storage field, harmonization of regulatory framework in EU, cooperation and synergies in R&D, ability to build new NPP with predictable costs and schedule, increase attractiveness for young people, etc., but the conditions highlighted above are the most critical at present. The ability to adapt to different energy mix scenarios requires on one side enhanced power manoeuvrability and load follow capabilities of the NPP's and on the other side better interaction with other energy

> *The ability to adapt to different energy mix scenarios requires better interaction with other energy technologies, particularly with renewables, with a view to identifying an optimal energy system integration.*

technologies, particularly with renewables, with a view to identifying an optimal energy system integration. The major social, environmental and economic aspects are in good compliance with the more general priorities specified in the SET Plan (EC, 2017) for the nuclear energy sector:

- Safety to help securing the long-term operation of existing nuclear reactors;
- Safe management of radioactive waste and decommissioning;
- Efficiency and competitiveness of current and innovative technologies.

Even wider view on the energy system and its 3 key pillars and issues gives the World Energy Outlook (IEA, 2018):

- **Affordability**
- **Reliability**
- **Sustainability**

The sad truth is, that after three flat years, global energy-related carbon dioxide (CO2) emissions are rising since 2017, far from a trajectory consistent with climate goals. SNETP together with its 3 pillars (NUGENIA, ESNII, and NC2I), in collaboration with EERA and its JPNM, can substantially contribute to most of the key tasks listed above, maintaining the safety and competitiveness of today's technologies; developing a new generation of more sustainable reactor technologies; and developing new applications for nuclear power.

> *SNETP together with its 3 pillars (NUGENIA, ESNII, and NC2I) (...), can substantially contribute to most of the key tasks listed above, maintaining the safety and competitiveness of today's technologies; developing a new generation of more sustainable reactor technologies; and developing new applications for nuclear power.*

4.4.2 State-of-the-art, Challenges, and R&D Topics

Safe operation and minimum impact on environment

In order to achieve safe operation in any power plant and in particular in a nuclear power plant, the following three conditions need to be met:

- A well established and implemented **safety culture;**
- Development and application of **state-of-the-art safety assessment tools and methods;**
- Consideration of **retrofitting** of **state-of-the-art** (passive) **safety features.**

Fission-based nuclear power has historically been one of the largest contributors of carbon-free electricity globally. The potential of nuclear power generation to contribute to the power sector decarbonization is significant. However, it should be noted that minimum impact on the environment must cover all phases of NPP lifetime and nuclear fuel cycle. Overall, EC (2012) shows that nuclear power generation has a low-carbon footprint and low direct plus indirect carbon emissions even considering the complete fuel cycle.

> *EC (2012) shows that nuclear power generation has a low-carbon footprint and low direct plus indirect carbon emissions even considering the complete fuel cycle.*

To that respect, the target to decarbonize Europe's economy by 95% by 2050, implying a major reduction in greenhouse gas emissions, calls for nuclear energy to remain a key source of electricity generation. The analyses of EC (2012) show that in all scenarios, centralized large-scale systems such as nuclear and gas power plants and decentralized systems will increasingly have to work together.

Economy and competitiveness

For the nuclear industry at large, it is a major challenge to make nuclear great again. In order to achieve this, long-term operation of existing reactors and deployment of new reactors should be facilitated. In principle, this should be achievable when modifications to existing plants and construction of new plants can be performed under a predictable schedule and costs. This will also mean that a fair economic playing field should be created for all low-carbon electricity generation and heat source supply systems. On top of that, investment risks should be mitigated and should be facilitated with national level investments. As an example, the strike price which is applied in the UK can be considered. On a levelized (i.e. lifetime) basis, nuclear power is an economic source of electricity generation, combining the advantages of security, reliability and very low greenhouse gas emissions (Deloitte, 2019).

In order to make nuclear more competitive from an economic point of view, the following R&D topics deserve attention:

- Deterministic and probabilistic safety assessments in support of enabling on-line maintenance with the goal to increase availability factors;
- Advanced deterministic and probabilistic safety assessment methods enabling optimization of safety margins and power uprates;
- Retrofitting of state-of-the-art (passive) safety features targeting better operational economy.

Social and political acceptability

The SET Plan (EC, 2017) identifies nuclear fission as one of the key low-carbon energy technologies. The intention is to 'maintain the competitiveness in fission technologies together with long-term waste management solutions'. To this respect, the benefits of nuclear fission should be presented, promoted and communicated in an open and transparent way such that the European citizens can educate themselves in nuclear knowledge and a continuous knowledge transfer takes place not only between experts and the public at large but also between generations. The public should be addressed on such a technical and controversial subject like nuclear fission in a professional way. Nuclear energy should be promoted and presented for what it is, i.e. part of the solution to the climate emergency, beyond prejudices, and in alliance with other low-carbon emission energy technologies, such as renewables, carbon capture and storage, hydrogen and fuel cells. To that respect the following R&D topic are identified:

- Collect technical facts and figures on benefits and drawbacks of nuclear fission. Obviously, a lot is already available, e.g. from organizations like the IAEA, OECD/NEA, JRC, SNETP and Foratom;
- Translate technical benefits and drawbacks into benefits and drawbacks the public at large can understand;
- Dialogue and ally with other low-carbon energy technologies in technical terms, identifying efficient and consensual ways of integration to be promoted together, as well as research issues of cross-cutting interest that can be faced together;
- Create a pan-European communication campaign allowing the citizens to educate themselves and take their own decisions.

Ability to adapt to changing conditions

Nuclear power plants can play an important role in a future energy mix given their compatibility with renewable energy sources and low-carbon footprint. This is underlined in many recent international studies including studies from EC (2011), MIT (2018), IPCC (2018), IAEA (2018), IEA (2018), and the OECD/NEA (2019), and the JRC (2020).

Including nuclear power plants in such a changing environment, in which fluctuating demands play a significant role through the increased application of intermittent renewable sources such as wind and solar power, poses new challenges on the integration of nuclear plants in the electricity grid. R&D topics will be:

- The impact of intermittent external loads including grid disturbances on safety functions of existing and new nuclear power plants;
- Demonstration and further improvement of NPP load following capabilities;
- The impact of new hazards (e.g. drone attacks, stuxnet viruses) on safety functions of nuclear power plants;
- Dialogue and integration with renewables and other energy technologies that aim at reducing greenhouse gas emissions.

5. CROSS-CUTTING TECHNOLOGIES

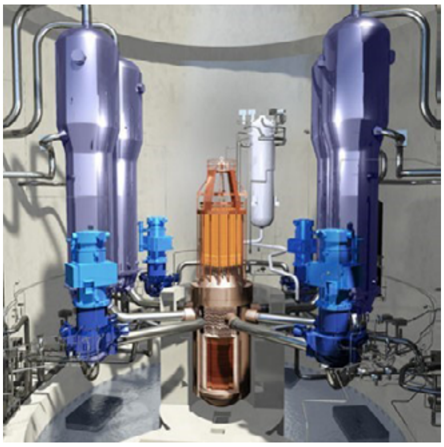
5.1 Digitalisation, Modeling and Simulation

5.1.1 Objectives and Motivation

Digital technology is an essential tool for the competitiveness of the nuclear industry as it is for other industrial sectors such as aerospace or automotive. All the three SNETP pillars are involved in this digital transformation, while EERA is creating a whole joint program devoted to these issues, transversal to all energy technologies. The main objective of digitalization, modelling and simulation is to increase safety and competitiveness for the operation and maintenance of existing NPPs and for new build. It will also enable improved cooperation between partners of the nuclear research sector.

The development in the field of modelling and simulation has to reach three goals:

- Adapt and accelerate the coupling between existing calculation codes by improving interoperability;
- Unify and make consistent numerical applications by linking the world of advanced expertise studies and industrial modelling;
- Benefit from breakthroughs in advanced visualization technologies (including virtual reality and augmented reality).



Digital nuclear reactor

> ***The main objective of digitalization, modelling and simulation is to increase safety and competitiveness for the operation and maintenance of existing NPPs and for new build.***

5.1.2 State-of-the-art and Challenges

Digital transition is not a totally new subject for nuclear. Digital tools have been widely used since the 1970s for the simulation and modelling of complex physical phenomena or for process control. Nuclear research has often been at the forefront of innovation mainly because of stringent safety requirements.

However, the current digital revolution encompasses new dimensions: the recent speed up of technological progress in terms of computing such as:

- **High Performance Computing** (HPC);
- **Artificial Intelligence**, e.g. machine-learning algorithms, deep artificial neural networks, gaussian processes and few-shot learning;
- **Virtual** and **augmented reality**;
- the extension of digitalization to the **entire life cycle** from the design stage up to the dismantling of nuclear units;
- the need for **digital continuity** to ensure that all stakeholders (i.e. nuclear operators, academia,

industry,..) can exchange information more efficiently.

Recent technological breakthroughs are for example the development of the Internet of Things and therefore the increase in data flow, significant development of Artificial Intelligence whether due to the efficiency of algorithms or to enhanced computing power. In terms of applications, digitalization will include reactor design (Generation III and IV) with advanced simulation tools, facility operation and maintenance via virtual imaging, augmented reality and artificial intelligence tools, and dismantling using robotic operations.

Considering modelling and simulations, the general trend can be summarized as **multi-scale, multi-physics, multi-phase plus uncertainty quantification.** Driven by progress in computational power and increasing understanding of separate processes, numerical simulations are expected to enter a domain of increased complexity. As a complement and enhancement or an alternative to physics-based simulation tools, data-driven modelling is currently booming, thanks to the progress made in data analysis using machine-learning techniques.

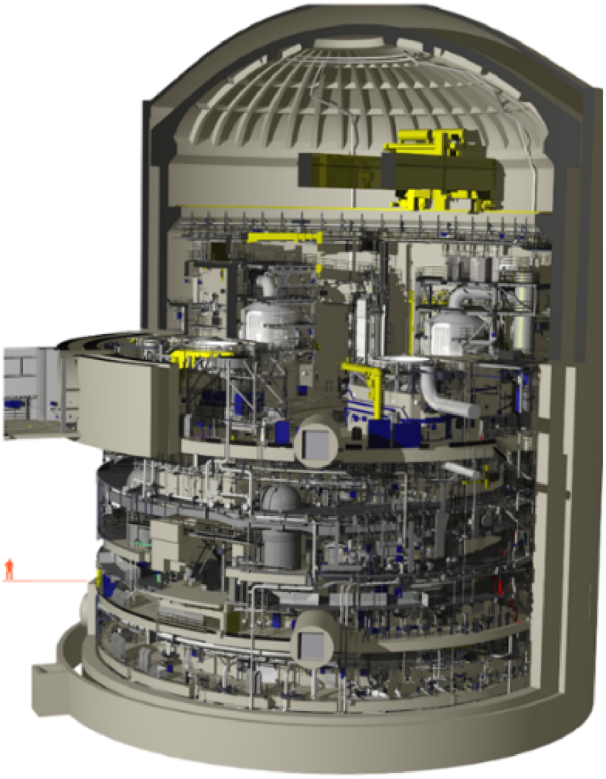
Multi-scale simulation refers to applying and possibly linking simulations of physical processes at the appropriate scales, e.g. atomic, microscopic, mesoscopic, component, system and plant scale. The development of tools operating at different scales aims at coupling simulation methodologies in single multi-scale packages. However, in this respect machine learning techniques offer the possibility of complementing a multi-scale modelling package, which will be most likely penalized by long computing times that are characteristic of high-fidelity simulation tools, with a single artificial intelligence-based tool, to be trained on multi-scale physics-based suites of codes.

Multi-physics simulation refers to linking simulations of different physical processes and domains, e.g. neutronics, thermal hydraulics, structural mechanics, fuel performance and chemistry. Here the key issue to link models consists in the identification of the variables coming from one domain that are needed for another domain. Because of the mutual influence, iteration is necessary and may be a bottleneck. In addition, because of the often local type of information that needs to be obtained, there is a conceptually unavoidable overlap between multi-scale and multi-physics approaches.

Multi-phase simulation is mostly used with reference to thermal hydraulic simulations and refers to the simultaneous simulation of various phases in which a substance can be, i.e. gaseous, liquid, or solid.

Uncertainty quantification is becoming more and more important and is expected to be requested by regulators for all kinds of safety analyses in the future. Specific digital technologies like artificial intelligence and cognitive computing have to work with advanced sensor technologies to address uncertainty quantification. This combination of technologies needs to be addressed if uncertainty quantification is to help improve reliability and safety. Uncertainty quantification for advanced and complex simulations with long run-times needs to be developed. In particular, in the case of multi-scale/multi-physics simulation, the development of appropriate and efficient methods for the evaluation of the uncertainty related to the choice of key parameters and its propagation through different simulation tools and models remains a challenge.

Such developments can be summarized as a major challenge for the nuclear industry being the construction of a European **digital nuclear reactor** in order to model the design, operation and maintenance, in normal or accidental operation for all kinds of nuclear technology, ranging from Gen II and III LWRs, to SMRs, and Gen IV systems. In fact, the goal is to simplify modelling and secure safety margins by a demonstration approach based on simulation. The use of a multi-scale, multi-physics, multi-phase digital reactor from the design stage is an innovative approach. As such, **digital twins** will gather on a large base several numerical and physical schemes, optimization models or uncertainties quantification techniques. As a rule, the basic elements (1D or 3D codes) are available among the nuclear community even though development is an on-going process. Obviously, **interoperability** of necessary modelling and simulation tools requires the development of simulation platforms, that should be provided with appropriate 'translators' to efficiently pass information between codes, possibly by-passing computing time bottlenecks by making use of artificial intelligence...



Nuclear twin
Photo: EDF

Human-Automation Collaboration for **Operation and Maintenance** is an open area for research by boosting digital innovation in support to the performance of nuclear operators in order to improve flexibility of nuclear units, prepare I&C upgrades, invent and test new operational concepts for new reactors such as SMRs. Challenges are technical with the development of digital twins reflecting the actual state of the facility as well as organizational (enhanced agility, resilience).

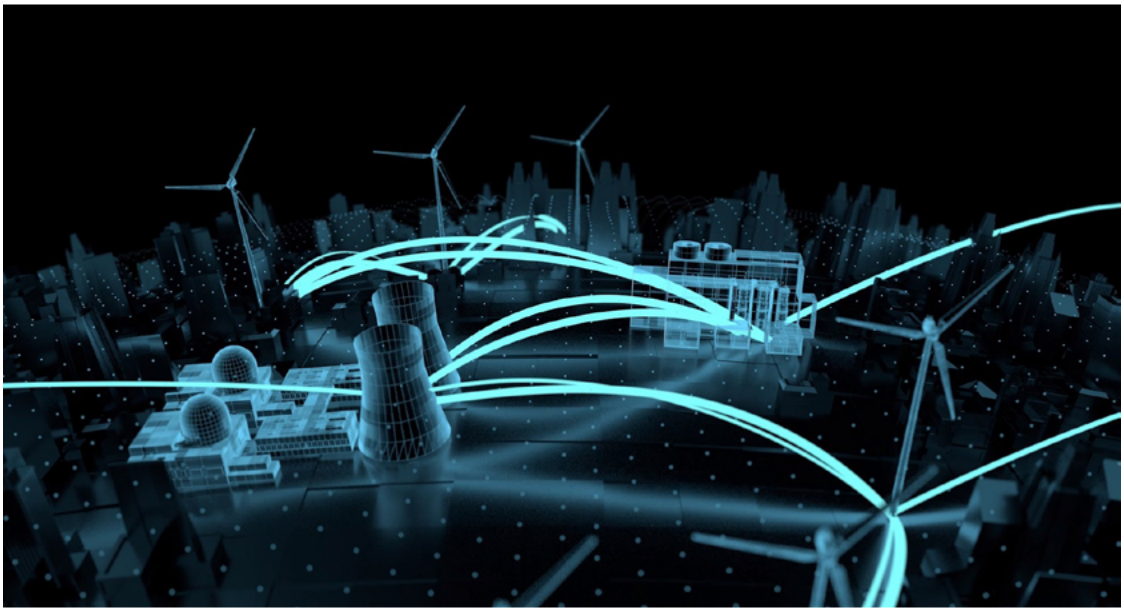
To analyse operation and maintenance data in order to optimize maintenance and replacement investments for large components in nuclear plants, **data analytics** tools have to be developed. Technical issues lie in the definition of robust indicators for the diagnosis of nuclear units (to obtain more reliable data and to process non-homogeneous and large data volume), and to determine duration of residual lifetime of components (monitoring data, physical degradation models). Developments in this area are of course connected with the capability of interpreting in a physically correct way the signals coming from sensors, which is in turn connected with the development of multi-scale and multi-physics models mentioned above.

A key enabling technology to all digitalization challenges lies in **cybersecurity**, making digital systems secure. The ultimate aim is to integrate cybersecurity from the design stage (from idea to completion) and to eliminate digital risks. One of the challenges is to integrate cybersecurity into all digital technology steps. The major hurdles lie in the introduction of new intrinsically secure technologies (e.g. programmable logic integrated circuits, network diodes) and in the effective detection of unknown or complex computer attacks by the combination of big data analysis tools and Artificial Intelligence.

5.1.3 R&D Topics

Sharing experiences and best practices in this field of a '**European Digital Nuclear Reactor'** should remove major scientific and technical hurdles. From a technology standpoint, it implies:

- Development and validation of **multi-scale** analysis tools for various kinds of physics ranging from material science, to thermal hydraulics, and chemistry;
- Development and validation of **multi-physics** analysis tools, coupling different physical processes, e.g. neutronics, thermal hydraulics, structural mechanics (with input from microstructural evolution predictions), fuel performance and chemistry. In first instance establishing a multi-physics tool coupling two individual processes will be required, however, since nuclear systems are highly interdisciplinary, eventually the goal will be the interoperability of multiple (if not all) physics analysis tools;
- Development and validation of **multi-phase** analysis tools for better understanding of multi-phase flow and heat transfer in a reactor which is an essential element in nuclear safety analysis and as such also important in the design phase;
- Development and validation of **uncertainty quantification** methodologies especially for complex long running simulations including multi-scale, multi-physics, multi-phase platforms, and its propagation through scales and methods;
- Development of methodologies to ensure **digital continuity** over the complete **life cycle** of a nuclear reactor, including methodologies in support of operation and maintenance;
- Determination of **robust indicators** through data-analytics for diagnosis of operation and maintenance of nuclear units and to determine duration of residual lifetime of components;
- Integration of **cybersecurity** in the digitalization process to eliminate digital risks throughout the life cycle;
- Increasing development and use of **artificial intelligence** through machine learning techniques to enable progress in all above fields: link and interface between scales and physics, removal of bottlenecks related with long computing time of high-fidelity simulation tools, development of artificial intelligence-based by-passes trained on physics-based packages, analysis of large quantities of data;
- Increasing development and use of **virtual** and **augmented reality** tools, particularly in support of design, operation and maintenance.



Photocredit: IAEA

All these developments will enable the development of **digital twins** of nuclear buildings and facilities. The objective is to address challenges of site optimization and of operators training through immersive preparation. Associated challenges in terms of R&D are to add ever more intelligence into digital models by using artificial intelligence and to broaden its use as much as possible to operational issues, with enhanced interaction by the use of virtual reality.

5.2 Materials

5.2.1 Objectives and Motivation

Although the needs may be somewhat different, research and development on structural (and a few functional) materials is of utmost importance for both operating reactors and future reactors.

In the case of current Gen II-III reactors, the materials are established and there is operational experience on their use for specific components, having therefore clearly identified most criticalities. There are precedents of replacement of materials in key components, such as steam generators. Moreover, the materials for the fuel assembly, especially for the cladding, are likely to be evolving in the near future to improve accident tolerance (see section 4.2). Finally, advanced Gen III LWRs may adopt incrementally optimized structural materials, if identified and available. However, the interest in new materials for current generation reactors is limited, even though some specific metallic alloys raise potential interest in perspective. What is mainly needed is an ever deeper knowledge of the rate at which degradation during operation occurs in the materials that are used in the reactor, in order to estimate and predict the residual life with increasingly greater precision and to assess the degree of safety of extended operation. This knowledge will improve the schedule of inspections, while moving towards a more and more automatized and continuous monitoring (see section 3.2), which becomes crucial for irreplaceable components such as the vessel, the containment and, in practice, cables as well. This knowledge will also be useful in connection with the need for component replacement. As a matter of fact, in an LTO perspective there is a need not only to predict the component life-time, but also to replace specific components. In order to optimize replacement and repair scenarios, reducing costs and possibly also further increasing the lifetime of the components replaced/repaired, advanced manufacturing routes are of specific interest. These fabrication methods are also expected to impact new LWR builds, reducing costs and including the possibility or modifying the design of some components for better efficiency. New builds may also adopt new types of concrete.

Regarding next generation reactor concepts, the development of new material solutions is crucial. This is so because of the use of non-aqueous coolants, with different compatibility features and requirements as compared to LWR, and the higher temperatures that are targeted (either for higher thermal-to-electricity conversion, or because of the goal of industrial heat production, or even simply as a consequence of the coolant requirements), as well as the high burnup that is aimed at. In the case of systems for which reasonable operational experience exists, e.g. the SFR or the HTGR, the materials solutions are more or less defined, thus the needs are mainly related with selecting, qualifying and codifying existing materials for the conditions expected in those reactors (pre-normative research), even though of course materials with improved high temperature resistance properties would certainly be of use, especially if they can be timely codified. However, for technologies such as the LFR, which has already reached a sufficient level of maturity to be designed and constructed, the identification and development of suitable materials solutions to enable temperature increase, while guaranteeing sufficient resistance to coolant attack, are key both for improved safety and economic viability reasons (similar considerations may be made for the SCWR). Finally, the feasibility of systems such as the VHTR, the GFR, and largely also the MSR, the technological readiness level of which is still joining techniques. The needs in the case of materials for future systems, particularly for fast reactors, are extensively discussed in EERA-JPNM (2019).

Concerning SMRs, while the materials issues are expected to be largely the same as in the case of their large-scale counterparts that use the same coolant and target the same operation temperature range, specific issues may arise in connection with the different size and the need for modularity. This may suggest material changes or require specific materials solutions, which should be identified and carefully looked into.

Irrespective of the different needs and challenges concerning current and future reactors, several aspects are of cross-cutting nature. These have been analyzed in some detail in EERA-JPNM (2019) and are summarized in section 5.2.3.

5.2.2 State-of-the-art and Challenges

LWR

The ageing management in view of LTO currently relies on four key stages:

1. Identification of systems, structures and components that are sensitive to ageing;
2. Examination of all SSC/ageing mechanism pairs retained in the form of an Ageing Analysis Sheet (AAS);
3. Elaboration of a Detailed Ageing Analysis Report (DAAR) for most sensitive components and structures;
4. Production of a Unit Ageing Analysis Report (UAAR) valid for the decade following the 3rd 10 year outage of each unit SSC long term O&M strategies.

These reports need to provide a diagnosis of the status of sensitive SCC and a maintenance planning, the prognosis for 60 years in view of LTO, including in particular the analysis of the risk of obsolescence (supplier loss, technology evolution, norm evolution…), SCC replacement and/or repair scenarios if relevant, and of course the corresponding investment planning. The challenge in connection with LTO is thus to improve the reliability of the prognosis to the number of years of life extension, while reducing conservatism and optimizing the replacement/repair scenarios in terms of investment needed. Relevant issues concern both replaceable and irreplaceable components. The strategy repeats itself component by component: understand mechanisms and develop reliable predictive models of materials ageing, NDE and online monitoring, establish robust criteria for integrity and fitness-for-service assessment, and improve materials solutions (or design if possible) in the case of replaceable components. The **replaceable components** affected (and the relevant issues) are mainly: reactor internals (irradiation assisted stress corrosion cracking, swelling and wear), duplex austenitic-ferritic steel pipe elbows (thermal ageing) and steam generator secondary pipes (fouling, clogging, stress corrosion cracking). The **irreplaceable components** affected (and the relevant issues) are mainly: reactor pressure vessel (embrittlement) and concrete containment (creep, drying and subsequent leakage). Finally, although not structural materials and strictly speaking not irreplaceable, cables and specifically the polymers used for cable insulation need to be included in the list of sensitive components: they are in practice irreplaceable, due to the incredibly large number of kilometers of them that are laid out in each NPP.

The most promising advanced manufacturing techniques for the replacement and in general the fabrication of nuclear components, as alternative to classical forging or casting, are based on powder metallurgy:

- Hot Isostatic Pressing (HIP) allows shape and material homogeneity and composition to be controlled and is especially suitable for heavy components. It is therefore currently considered for the replacement of elbow pipes, that have been so far produced by casting. In the future this method may enable the fabrication of pipes with integrated nozzles (thereby minimizing the need for welds) and of components that need superior wear resistance (by suitably choosing the powder composition on the surface);
- Additive Manufacturing (AM) is especially suitable for components of complex geometry, but currently limited in terms of component size. It is therefore considered for small components with complicated shapes, for which suppliers are often difficult to find.

Both techniques offer the possibility of reducing manufacturing delays when obsolescence occurs, with the possibility of improving the design, because the shape of the component is not any longer limited by manufacturing. However, several R&D challenges remain before the application in nuclear industry can become a reality:

- Improve the controllability and reproducibility of the process, understand how the process limits the final component/materials properties and its correlation with the type of microstructure and thus properties obtained;
- Improve the component quality (especially in the case of AM), in terms of homogeneity, minimal porosity, correct density and microstructure, minimal residual stresses (by suitable post-treatment), etc.;
- Demonstrate compliance of the final product with nuclear requirements (regulators), verifying that the ageing behavior (e.g. resistance to irradiation and corrosion) is comparable to components fabricated with traditional methods.

It has to be emphasized that these techniques make the material properties related to the type of component that is fabricated, because this will influence microstructural features, porosity, residual stresses. Therefore, the standards for the qualification need to be developed not really for the material as such, but actually for the component made with a certain material according to a certain process. The materials of interest are mainly austenitic stainless steels and nickel-based alloys, as well as, to a lesser extent, zirconium alloys.

In terms of improved nuclear safety, the main challenge for Gen II & III reactors is accident tolerance, which implies improved fuels but especially, in practice, cladding materials with higher thermomechanical stability. The objective is to design and qualify fuel casings that can remain intact for a sufficiently long time even when subjected to the high temperatures and mechanical stresses typical of a nuclear accident. Accident tolerance is intrinsic to HTGRs and is being developed for LWR, but the concept will have to be extended also to fast reactors and other innovative reactors. The material solutions proposed range from chromium-coated zirconium alloys to refractory metals and ceramic composites. These materials require, in order to be adopted and used in reactors, all the necessary qualification, thereby calling for an accelerated qualification process.

Advanced reactors

The deployment of advanced reactors requires demonstrators and prototypes to be built as first steps. These are not expected to include all the features of true Generation IV systems, but are meant to be a step in that direction, generally through different phases. Since the main limiting factors in terms of component lifetime are temperature, coolant attack and irradiation, for which in most cases suitable materials are not available. The idea is to start with relatively modest temperature and also irradiation levels, to be increased in subsequent phases. In this way the research on materials can be split into several steps or stages from the initial one to the final one, which can be denoted as near term and long term, with intermediate stages in between. The classes of materials that are expected be used to design and construct advanced reactor demonstrators, prototypes and then commercial reactors, including the different intermediate phases, have been analysed in detail in EERA-JPNM (2019).

In the near term, materials for which operational experience already exist will be used. These will be exposed, taking as example the LFR demonstrator, to temperatures not higher than 400°C, and negligible neutron damage, in the case of the main vessel, and to temperatures between 450°C and 500°C, subject to weak neutron damage, in the case of the internals of the reactor. Even the core structures, unavoidably exposed to intense neutron damage, will not exceed 550°C as maximum operating temperature. This approach allows material R&D in the first phase to be limited, the fuel elements being replaced with a frequency higher than the standard, in order to better control the damage evolution, allowing the qualification of materials for the next phases.

> ***The deployment of advanced reactors requires demonstrators and prototypes to be built as first steps.***

The materials of interest for all fast reactor demonstrators, on which the qualification and pre-normative research effort needs to be mainly focused, are austenitic stainless steels for structural functions, such as 316L nickel-based alloys are considered for some out-of-core applications, while for some specific components of specific designs, ferritic/martensitic steels have also been chosen. Ceramics composites (mainly silicon-carbide (SiC) fibers) will be necessary for the high temperature operation of e.g. a GFR demonstrator, but these materials are currently still far from being fully qualified, therefore even in this case for the demonstration lower temperatures and known materials will be most likely used. Surface protection may be necessary already for demonstrators to provide sufficient compatibility with coolants, especially in the case of the LFR.

Improvements of safety, performance and economy in future prototypes and then commercial reactors advises the exploration of improved (more swelling resistant) austenitic steels, advanced (creep-strength enhanced) ferritic/martensitic steels, refractory alloys, oxide dispersion strengthening via powder metallurgy, advanced surface protection methods (from ceramic coatings to self-healing protections by addition of aluminium to the steel compositions: alumina forming austenitic steels, and ferritic iron-chromium-aluminium steel) and, for the longer term, prospective materials such as high entropy alloys or so-called MAX phases. Especially challenging is the development of a methodology to accelerate material development, screening and qualification. In the absence of such a methodology, innovation in the field of nuclear materials will require decades, i.e. too long times to be flexible and competitive.

In the long term, the challenge for the materials is to bring the maximum temperatures of the thermal cycle of the reactor closer to the boiling temperatures that characterize the non-moderating coolants: ~880°C for sodium, ~1700°C for lead and further higher for the helium. An ambitious but reachable target for SFR and LFR could be placed at 750°C for core structures, and 650°C for internals. In the case of GFR, the target temperature should be set at 900°C. At this stage the R&D carried out during the previous stages will have allowed the complete qualification, even under neutron load, of at least some among the most promising materials mentioned above. The qualification must also include suitable welding and junction methods.

5.2.3 R&D Topics

LWR

In order to reduce conservatism in the margins currently used for the safety assessment of existing LWR components, it is necessary to develop advanced fracture mechanics approaches and new methods for environment assisted fatigue assessment, that guarantee transferability from specimen to component. The former applies especially to the reactor pressure vessel (RPV, see below), but also to the turbine blades and disks or to the cylinder heads of the diesel engines. The latter applies to hydraulic thermal mixing zones, stratification zones, flow distribution baffle of the steam generator, etc. In order to optimize replacement/ repair scenarios, a number of challenges can be identified, that are related to specific classes of components:

01

REACTOR INTERNALS:

- Model irradiation assisted stress corrosion cracking (IASCC) using a multi-scale, multi-physics approach, that should include thermo-hydraulics, neutronics, materials microstructural processes and mechanical conditions of the component (stress distribution). Models should allow IASCC susceptibility to be evaluated, especially in baffle bolts;
- Develop an overall assessment procedure to guarantee the efficiency of tube guides, which should include test and modelling of swelling effects, test and modelling of wear and improved resistance against it (new materials solutions), as well as effects of vibrations due to thermal-hydraulics.

02

DUPLEX AUSTENITIC-FERRITIC PIPE ELBOWS:

- Develop a methodology that enables a correct residual lifetime prognosis, by designing 60-year-equivalent thermal ageing program and subsequent characterization and an appropriate NDE scheme (e.g. thermo-electric effect measurements);
- Evaluate alternative solutions, such as: regeneration of material properties by thermal treatment, use of powder metallurgy (Hot Isostatic Pressing, HIP) for austenitic-ferritic cast iron elbow replacement.

03

STEAM GENERATORS AND SECONDARY PIPES:

- Extend the service lifetime by better understanding and modelling, and thus preventing, fouling/ clogging, as well as stress corrosion cracking.

In order to perform a correct residual lifetime assessment for irreplaceable components, a number of component-specific challenges stand out as well:

01

REACTOR PRESSURE VESSEL:

- Develop physics-based models for RPV lifetime prediction in terms of fracture toughness degradation (embrittlement), as a consequence of irradiation and thermal ageing;
- Use the knowledge of fracture toughness degradation to assess the RPV resistance to a pressurized thermal shock in case of a loss of coolant accident (LOCA);
- Gain margins in terms of thermo-hydraulic loading, in case of a LOCA, by using 2-phase flow CFD simulation and crack analysis with warm pre-stress effect, as well as by improving NDE of RPV nozzle welding;
- Improve thermal hydraulic analyses of PTS by coupled system and CFD computer codes;
- Gain margins in PTS analysis with warm pre-stress effects;
- Improve non-destructive examination of the reactor pressure vessel.

02

CIVIL ENGINEERING BUILDINGS (CONCRETE OF CONTAINMENT):

- Guarantee long-term tightness by combining leak rate tests, cement and concrete testing, suitable NDE technology and appropriate maintenance strategies, while developing tools to simulate concrete ageing (creep, drying, ...) and the mechanical behaviour of the reinforcement bars.

Concerning cables, in order to guarantee life extension beyond 40 years, tools need to be developed for a robust demonstration process. Similar to the case of RPV and containment, these include physico-chemical modelling of polymer ageing due to temperature and irradiation, NDE and monitoring of cables and related diagnostic methods and criteria for qualification and fitness for service.

Advanced reactors

The R&D materials topics related with advanced reactor systems are necessarily broader and less specific than in the case of LWRs, because the relevant operational experience is limited. Thus what is needed is first and foremost the qualification of the candidate demonstrator materials (mainly austenitic steels of the 316L family, and 15Ni-15Cr titanium stabilized for the cladding), or materials solutions (e.g. ceramic coatings on top of traditional materials, for greater resistance to the chemical aggression of the coolants), for the correspondingly expected operating conditions. The construction of demonstrators is expected to be the crucial step that will subsequently trigger and open the way to the identification and qualification of materials that allow the following phases to be addressed.

In perspective, the requirement of 60 years design lifetime for non-replaceable components is the most demanding requirement, which includes under its umbrella several R&D issues, that are related with the reasonable prediction of long-term degradation processes. These include:

- High temperature processes (creep, fatigue, thermal ageing);
- Compatibility with (heavy) liquid metal and helium coolants;
- Effects of low flux prolonged irradiation.

Emphasis is on welded components in all cases.

In terms of testing, there is a need for standardization, especially for sub-size and miniature specimens. The modelling, from atomistic simulations, through mesoscopic approaches up to macroscopic constitutive models, supported by advanced microstructural and mechanical characterization, has as its main objective the development of suitable microstructure evolution models to be used as input to models for the mechanical behaviour under irradiation and at high temperature, eventually linking with fracture mechanics. Specific developments are required for coolant compatibility models, as well as for models in support of the use of charged particle irradiation for the screening of new materials solutions.

Cross-cutting

Overall, the following R&D issues can be considered cross-cutting through different reactor generations:

- Advanced manufacturing in broad spectrum methods will benefit both current and future reactors;
- Any activity related with understanding physical mechanisms and developing relevant models, by this meaning multi-scale modelling, use of artificial intelligence, application of accelerated exposure techniques such as ion irradiation for specific studies, and the relevant methodology, are common;
- Materials with better resistance to high temperature and corrosion after irradiation, which are a must for advanced reactor systems, can also be beneficial for future LWR, especially in an improved accident tolerance framework (most candidate ATF cladding material coincide with candidate cladding materials for advanced reactors, ranging from creep-resistance enhanced steels, ferritic or austenitic, to refractory alloys and ceramic composites);
- Methodologies related with materials qualification, especially of welds and joints, internal stresses evaluations and online monitoring at large, are beneficial for all reactor generations, despite differences in the specific application. Small specimen size testing can be included in this list, for better exploitation of limited irradiation facilities and limited space in them. The qualification of components fabricated using advanced manufacturing techniques require global qualification methods, given that the properties of the material are not independent of component manufacturing process, shape and type: here, too, the methodology to be developed and applied is common;
- The use, and therefore maintenance and coordinated planning, of nuclear materials exposure and testing infrastructures is also of common interest, notwithstanding neutron spectrum differences depending on the target technology (see section 6.1).

It is finally important to emphasize that many of the above reactor generation-common issues, as well as those related with compatibility with heavy liquid metals and gases for advanced reactor systems, are cross-cutting with nuclear fusion materials. Furthermore, structural materials with superior corrosion and temperature resistance that may be developed for nuclear applications have a potential, as happened in the past, to be of use for other energy technologies where high temperatures and corrosive fluids are part of the picture, such as concentrated solar power, geothermal energy, fuel cells and bioenergy.

6. NON-TECHNOLOGICAL CROSS-CUTTING ASPECTS

6.1 Research Infrastructures

6.1.1 Objectives and Motivation

Graphic representation of how the PALLAS reactor building will look

EC (2019) underlines the need to ensure availability of state-of-the-art research infrastructures (in particular for materials research and innovation, irradiation facilities, nuclear safety, research reactors and hot cells). Current initiatives in France with the Jules Horowitz Reactor (JHR, http://www-rjh.cea.fr/), in Belgium with the MYRRHA initiative (https://myrrha.be/), and in the Netherlands with the PALLAS reactor (https://www.pallasreactor.com/) should get political support from all SNETP members ensuring at the end of the day sufficient financial support to realize these capital intensive projects which have a large impact on the future of the European nuclear research infrastructure. An important boundary condition is a financially sound basis for the operation of the infrastructure. Current-day models do not sufficiently account for the increasing costs imposed by measures in the field of, among others, security and waste handling, endangering access and availability of these infrastructures.

6.1.2 State-of-the-art and Challenges

As a starting point, a 'picture' can be taken of the current situation. This describes the state-of-the-art. Such 'pictures' mostly result in a database of existing and (near) future infrastructures in certain domains of interest. Around the year 2010, the OECD/NEA took an initiative create a database of research infrastructures for gas and sodium cooled fast reactors documented in OECD/NEA (2009) and (2010). In parallel, the European collaborative project ADRIANA made databases of research infrastructures for fast reactors documented in ADRIANA (2011). More recently, an initiative was taken by NUGENIA to collect a database of research infrastructures for light water reactor applications which is available as NUGENIA (2016). This NUGENIA database contains more than 180 experimental facilities amongst which Material Testing Reactors, critical mock-ups, training reactors, hot cell laboratories, chemistry-corrosion labs, mechanics-materials labs, measurement labs, severe accidents setups, and thermal-hydraulics test loops. And finally, the IAEA (2018) documents research infrastructures for liquid metal cooled reactors. With respect to these databases, the main challenge is:

- Collecting, updating and maintaining research infrastructure databases internationally at one place.

Nevertheless, a database is just a starting point. More important is to maintain and upgrade the facilities themselves and to construct new ones if

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there is a need to. As mentioned before, an important boundary condition and main challenge is:

- Creation of a financially sound basis for the operation and maintenance of these infrastructures.

6.2 Harmonisation

6.2.1 Objectives and Motivation

As stated in Nuclear Illustrative Programme (EC, 2017), the construction of new nuclear units will be necessary in the future in Europe to satisfy the energy objectives of the European Commission (EC). This program encourages vendors and suppliers to engage in an initiative to standardize their components and codes to a higher degree in order to ensure:

a. a faster procurement process;

b. higher compatibility and more transparent and higher safety standards;

c. increased capacity of operators to control technology and knowledge management.

Among them, the most challenging task is harmonization of safety standards. Because nuclear safety is a national responsibility, national regulators are independent and we face 29 different sets of safety rules in EU. It is not widely appreciated yet, that the independence of judgement does not exclude cooperation in preparing or harmonizing safety standards. Below we mention some initial efforts, but they are by far not enough and further cooperation between regulators should be encouraged.

This is especially important for Generation IV innovative reactors. LWR standards have been developed over many years from practical experience and therefore they are at least conceptually coherent between different countries. This is certainly not the case for advanced reactors. There is a risk, that regulations concerning advanced reactors will be so different that the EU market will be split into several regions requiring different designs. This might be an important barrier in deploying Generation IV reactors in Europe.

> ***Because nuclear safety is a national responsibility, national regulators are independent and we face 29 different sets of safety rules in EU.***

6.2.2 State-of-the-art and Challenges

EUR Requirements

One of the first initiatives in Europe to standardize nuclear reactors and harmonize safety requirements was launched in the early nineties when the main European nuclear utilities that were considering building new reactors in the 21st century, convened to establish common design targets directed to potential reactor vendors interested in the nuclear European market and formed the European Utility Requirements (EUR) organization. Interested vendors submitted applications for their products to be assessed by the EUR organization through a comprehensive process to analyse the degree of compliance with these requirements. Several reactors types have been assessed including the reactors from AREVA, Westinghouse, GE, AEP Moscow, and most recently from Mitsubishi and CGN. The EUR document has been used by some utilities to define technical specifications associated with their call for bid of nuclear projects. It is regularly updated to integrate new knowledge, the feedback from the assessments and the evolution of regulatory requirements. The last version (revision E) comprises more than 4500 requirements and integrates the lessons learnt from the Fukushima accident.

WENRA Reference Levels

Another initiative came from the European regulatory side in the early 2000s, when the WENRA organization was created to define common safety requirements (termed Reference Levels) applicable to reactors operating in Europe. Although these safety requirements are not legally binding, all members of WENRA are committed to include them in their national regulation. In November 2010, WENRA published safety objectives of new nuclear plants so that the new plants will be even safer than the existing ones and these news plants will have very high and comparable levels of safety.

EU Nuclear Safety Directive

In 2009 the European Union issued a Nuclear Safety Directive that established high level safety principles and a common regulatory safety framework. This Directive was subsequently updated after the accident at Fukushima to include safety objectives consistent with the WENRA requirements as well as some new technical ones.

ENEF Roadmap Towards European Reactor Design Acceptance

In 2011, at the request from the European Commission, and in the framework of the European Nuclear Energy Forum (ENEF), a report was produced to make progress in harmonizing licensing processes in Europe. This report, entitled “Road Map Towards European Reactor Design Acceptance”, aimed at allowing deployment of standardized reactors in Europe through harmonization of licensing processes. This ENEF report makes recommendations to develop in national licensing regulations “stand alone design reviews” where a design could be assessed independently of a specific project, with a process similar to the Generic Design Assessment in the UK. It also suggests European regulators to closely work together in reviewing a design proposed by vendors and to conduct joint assessments. The report calls also to the European nuclear industry to harmonize industrial nuclear codes and standards. These industrial codes and standards define how to comply practically with safety requirements of higher level. Although design codes are mainly developed by industry, the regulators rightfully want to approve them as they are the basis of the detailed design and construction activities, or at least to assess their compliance with national regulations.

6.2.3 R&D Topics

The main challenges for SNETP in the harmonization field can be identified along several initiatives.

Harmonization of the codes and standards

Taking the nuclear codes of AFCEN (e.g. RCC-M) as a starting point, since 2014, AFCEN intends to explore a generic pattern for “Europeanized” codes that can be adopted for any nuclear project in the EU, primarily for new build but also potentially for improvement and life extension of existing nuclear facilities. The workshop is organized with three specialized “prospective groups” covering a specific technical area addressed by the AFCEN code and based on the above-mentioned structures:

- PG1: mechanical equipment for Generation II and III reactors (with reference to the RCC-M code);

- PG2: mechanical equipment for Generation IV reactors (with reference to the RCC-MRx code);
- PG3: civil works (with reference to the RCC-CW code), covering Generation II and III as well as Generation IV.

Continuation of the work through a follow-up that will take into account the experience of the present phase in order to exploit the work done in phase 2 and further improve its process should be considered with a view to:

- Include more reference to non-nuclear high quality industrial standards;
- Enlarge the scope to take into account in service inspection and life management;
- Link between the safety class of Structures, Systems and Components and quality requirements.

In order to enhance the harmonization of the Design Codes at EU level, the AFCEN research and development proposals need to be taken into account.

Partnership with other industry

Modernization and optimization of the European nuclear industry supply chain

The European Commission held a seminar on 28th October 2016 in Brussels in order to support the project based on the modernization and optimization of the European supply chain for nuclear components. The 20th of March 2017 the task force examined the term of reference of the workshop. The goal of the proposals is to modernize and optimize the European nuclear industry supply chain by ensuring that the European nuclear industry benefits from the rapid developments and technological possibilities offered by the non-nuclear industries as well as the non-European nuclear industries, while still guaranteeing the harmonized European nuclear safety level. This requires a mutual recognition and presumption of conformity of simplified processes by which compliance can be shown, between the world of the safety requirements and the physical world of the safety class SSCs.

Greater use of High-Quality Industrial Grade Items in European Nuclear Installations

The trade association for the European nuclear industry, FORATOM established a Supply Chain Optimization Working Group (SCOWG) to explore challenges and current industry practices to optimize the supply chain. Throughout 2019 the SCOWG have conducted activities in this field and will in 2020 publish a report outlining how greater use of high-quality industrial grade items in nuclear installations via a common European harmonized way is a means to further enhance safety, competitiveness and availability of the nuclear industry.

Benchmarking Nuclear Technical Requirements

Benchmarking of nuclear technical requirements against WENRA safety reference levels, EU regulatory framework and IAEA standards should take place in order to contribute significantly to more rapid and generic licensing of nuclear new builds and to extend the operational life of existing reactors. To achieve this, the following initiatives are taken:

- Benchmarking of the EUR documents against all applicable WENRA reference levels IAEA standards and the of the amended directive on nuclear safety as detailed by the EC;
- A feasibility study to extend the ETC nuclear codes of AFCEN to other national legal frameworks and other type of reactors than the EPR;
- A detailed description of the technical content that **an EU common pre-licensing process** should include, taking into account the different types of reactors, the applicable safety standards and the diversity of Member States national framework;
- A set of **technical reference guides for LTO should be prepared covering in particular aspects related to the safety upgrades.** In addition, a benchmarking of national LTO programs against the amended directives will be defined and described particularly regarding art 8a and 8b of amended nuclear safety Directive, for future use by regulators.

This study has been submitted through a call for tenders in November and December 2016. The study started in July 2017.

Analysis to support implementation of Articles 8a–8c of Council Directive 2014/87/Euratom

This project is part of the European Commission's activities to support EU Member States, competent regulatory authorities, and licensees in the effective implementation of Council Directive 2014/87/Euratom by facilitating the sharing of experience, and to **promote more consistent and ambitious implementation of these provisions at the EU level.** For this purpose, the Commission is already working with Member States and competent regulatory authorities (notably through ENSREG) to discuss national approaches and to identify further work to support more convergence in the implementation of the nuclear safety objective. This project is complementary to the activities with ENSREG and designed to inform and identify future areas of work and priorities of the European Commission in that context. This study is ongoing since beginning 2018.

OECD NEA Nuclear Innovations 2050 (NI2050)

The goal of the exercise launched by the OECD/NEA is to identify areas of most needed or most promising innovations and to find a way to speed up their route to practical applications. The first goal has been already achieved, while the second one is just about to be addressed. Among the priorities identified by NI2050 are development of common licensing framework for High Temperature Reactors (HTR), and acceleration of procedures for new fuel qualification based on advanced modelling and development of suitable structural materials for advanced reactor applications. Following the contribution of SNETP/NC2I, a possibility of launching an international common project on the first issue is being considered by the OECD/NEA, while the activities concerning fuel and structural materials, the latter largely in connection with the EERA-JPNM, are mainly being addressed through fora devoted to coordinate irradiation programs, as well as delegating activities to NEA working parties.

IAEA activities

The International Atomic Energy Agency conducts several activities related to safety requirements for advanced reactors. Among them is the Technical Working Group on SMR's. In November 2018, the IAEA published a common report with GIF titled "Safety of High Temperature Gas Cooled Reactors".

Initiatives follow-up and Challenges

Support to the aforesaid initiatives emphasizing their potential contribution to the improvement of rules, practices and methodologies will be beneficial. The valorisation by SNETP will include exploitation of these projects results. For doing that, SNETP will rely on a systematic and continuous dialogue among the stakeholders of the projects.

6.3 Education, Training and Knowledge Management

6.3.1 Objectives and Motivation

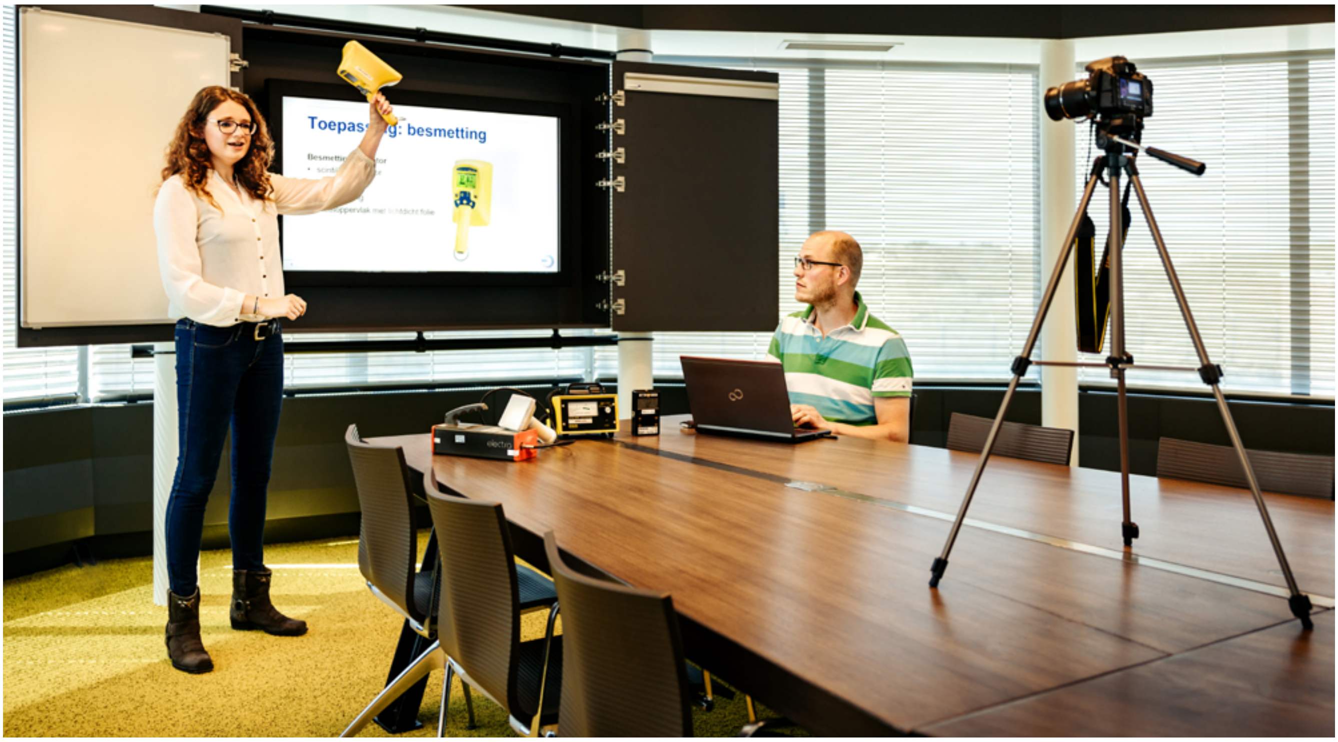
High quality education and training are vital aspects of any sustainable nuclear energy program. They require universities and training organizations to work together with industry and regulators, as well as governments in some countries, to ensure the required quality and quantity of the workforce. The first signs that nuclear higher education might be dwindling were noted and reported in high-level documents at the end of the 20th century. These documents included comprehensive sets of bottom-up and top-down recommendations to preserve and improve nuclear higher education and training.

Many initiatives followed, including the establishment of the ENEN Association in 2003, and enabled mainly 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 15 years through projects by the European Commission. Many of the suggested top-down activities were unfortunately never attempted.

Nearly 20 years after the first signs of dwindling nuclear education, the main concerns persist. It is noted that nuclear energy currently has varying degrees of support in the countries of the European Union but education and training is required across all three phases - construction, operation and decommissioning - of a nuclear plant. It is therefore imperative that education and training programs exist to support the full life cycle of nuclear power plants.

As well as the initial qualifications from apprenticeships to doctorates, lifelong learning through continual professional development is also very important to ensure that the nuclear workforce is suitably qualified and experienced.

Another educational aspect is related to the low level of acceptance in today's society. One possible reason for this low acceptance is an anti-nuclear mindset which is not reasonably justified but partly emotional. The mindset of people, however, is started to be formed in elementary school and secondary school. Establishment of a pan-European fair education framework allowing for a better based and more widely spread understanding of power generation challenges and costs would be advised. The final objective would be to create a reasonable awareness of the necessity and boundary conditions of electricity generation, allowing people to make their own choices based on a fair educational framework.



Nuclear education in the Netherlands
Photo: NRG (2019)

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

6.3.2 State-of-the-art and Challenges

Over the last fifteen years one of the main drivers for the development of nuclear education and training programs throughout Europe has been the European Nuclear Education Network (ENEN – www.enen.eu). The seventy-five members of ENEN:

- promote collaborations to support high quality nuclear education;
- increase the attractiveness of nuclear education and training for students, researchers and professionals;
- promote life-long learning and career development at post-graduate or an equivalent level.

Organizations working together 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 topic areas are developed equally.

This coordinated approach to the networking of nuclear education and training in Europe has now been mirrored in other regions. 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;
- **LANENT** – Latin American Network for Education in Nuclear Technology;

- **AFRA-NEST** - AFRA-Network for Education of Nuclear Science and Technology;
- **STAR-NET** - Regional Network for Education and Training in Nuclear Technology.

Recent initiatives funded by the European Union to support the continuous growth and development of nuclear education and training have included ANNETTE (Advanced Networking for Nuclear Education and Training and Transfer of Expertise - www.annette.eu) and ENEN+ (plus.enen.eu).

A key aspect of ANNETTE is the coordination of existing activities in nuclear education and training in order to:

- connect E&T groups of existing Platforms (SNETP, IGDTP, MELODI, EAN, EURADOS, EUTERP, Alliance, NERIS, the medical platforms, EFOMP and others);
- make an inventory of existing E&T initiatives, mapping how different projects are connected in order to identify overlaps and gaps;
- connecting existing singular databases into one database for E&T initiatives adapted to the needs of every Platform;
- support education and training initiatives outside of the European Union, in connection with IAEA and other relevant groups.

With these goals ANNETTE aims to enhance nuclear knowledge, skills, competences and thus enhance nuclear safety culture.

ENEN+ builds on the success of the first fifteen years of the European Nuclear Education Network (ENEN) and aims to convert the interest of the young generation into nuclear careers by pursuing the following main objectives:

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

The ENEN+ consortium focuses on learners and careers in nuclear reactor engineering and safety; waste management and geological disposal; radiation protection and medical applications.

ANNETTE and ENEN+ are the current activities in the two-decade long EURATOM Fission Training Schemes (EFTS), which are strongly supported by the European commission. EFTS are built on the principles of common qualification criteria, common mutual recognition systems, and the facilitation of teacher, student and professional mobility across the EU. To date, they have already resulted in a wide range of measures targeting the development of nuclear E&T programs at universities, research institutes and industrial training providers.

However, despite the remarkable results obtained since the launch of the EFTS initiatives in early 2000s, it must be recognized that the enrolment of students to nuclear disciplines has not yet reached the desired level. A plausible explanation lies in the fact that rather than direct support to the recruitment most efforts have been directed towards creation, improvement and harmonization of E&T programs, establishment of adequate schemes and frameworks for professional development, pooling of resources and means at European level, organizational restructuring and capacity building. These initiatives were indeed greatly needed as a premise to reach expected goals, e.g. for maintaining and transferring the expertise of nuclear professionals. It is now time to consider at its very roots the pipeline of nuclear workforce, tackling the problems discouraging young students from selecting nuclear subjects as their choice for a future career.

Main Challenges

An in-depth analysis by Chung (2018) of Kyung Hee University in South Korea points to some very plausible reasons for the persistent concerns, including:

✓ Tendency to solve the easy problems first;

✓ Tendency to be more concerned about 'how' and 'what' then 'why'.

These reasons are consistent with the experience and observations of ENEN.

'Why' is usually associated with curiosity, knowledge, higher education, research, and academia. Similarly, 'how' and 'what' may be associated with needs, training, skills, experience, knowledge management, industry and knowledge communities.

High tech industry, including nuclear, depends on people with very diverse degrees of education and training. Search for efficiency, stimulated in part by pressures from competition, might guide the industry towards more internal training, directed naturally much more towards 'what' and 'how' than 'why'. In other words, dwindling of the higher education might be compensated for a short while with more intensive training by the industry. In the short term, such a focused approach may even increase the safety record of the industry.

In the medium and long term, too much focus on 'what' and 'how' may have some unexpected and unwanted consequences, which develop gradually and intensify with time. One consequence is the lack of innovation and the subsequent loss of competitiveness and the interest of young creative talents. Another is possibly the perception of poor transparency towards the public. This may develop when the institutions dealing predominantly with 'why' do not have sufficiently detailed insight in the activities of the industry.

One may also say that dealing predominantly with 'how' and 'what' is easy, as it mostly requires the stakeholders to follow the market conditions only. The 'why' may be seen as more difficult, as it must fit the boundary conditions dictated by the market, but also requires long-term strategic planning, communication, cooperation, strategic (long term) investment, etc.

Attractivity or Complexity

Many 'knowledge communities' have developed over the decades of nuclear electricity production. Many of them have already approached ENEN for cooperation and coordination. These include nuclear engineering, radiation protection, management of radioactive waste, fusion engineering, medical applications, nuclear security, nuclear safeguards, nuclear materials, nuclear safety assessment, nuclear culture for safety, radio chemistry and decommissioning of nuclear installations. Some of them have not yet sought cooperation or coordination. The most important among those might be the nuclear regulatory community.

Increasing the complexity of technology and concerns about the existing education and training are among the main reasons leading to the development of the knowledge communities, which became more and more independent from each other. The possibly unwanted consequence is increased complexity - and reduced attractivity - of nuclear education and training.

> *Increasing the complexity of technology and concerns about the existing education and training are among the main reasons leading to the development of the knowledge communities, which became more and more independent from each other.*

Competition or Cooperation

Another possibly unwanted or unexpected consequence of the stronger and more independent nuclear knowledge communities is competition for talents between nuclear communities rather than cooperation of nuclear communities in competition for talents with other complex or high technologies.

Steady supply or highly cyclic demand

Experience shows that construction of nuclear power plants comes in waves (e.g. in Europe 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, assuming that every nuclear power plant is with us for a century or more, repeated also in the future. Between those waves, the demand for the new personnel is generally very limited.

In general, the (high) educational systems need sustainable and stable conditions and might need very specific support for the times with low demand to avoid university departments being shut down on the grounds of too low demand 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).

6.3.3 R&D Topics

The bottom-up approaches to revive the nuclear education and training practiced during the last two decades were, on the whole, satisfactory to maintain the education systems and generate warnings to the decision makers. They were unfortunately not satisfactory to attract many new talents and did not lead to substantial innovations to nuclear (power) technologies. The proclaimed closures of operating plants in many countries may contribute to further dwindling of nuclear education. Top-down (strategic) approaches are needed to maintain and further develop the nuclear education and training. This includes for example the policy studies to review current and planned future activities and development and implementation of nuclear education, training and knowledge management strategies consistent with the long-term visions/plans for development and implementation of nuclear technologies. ENEN is, as a part of the ENEN+ project, working on a European strategic agenda for nuclear education, training and knowledge management. This document will be offered as the basis for discussion to all nuclear stakeholders and will hopefully serve as the basis for a joint action of all nuclear stakeholders.

> *Top-down (strategic) approaches are needed to maintain and further develop the nuclear education and training. This includes for example the policy studies to review current and planned future activities and development and implementation of nuclear education, training and knowledge management strategies consistent with the long-term visions/plans for development and implementation of nuclear technologies.*

Conclusion

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.

6.4 Global outreach of European SRIA

According to the IAEA PRIS database, there are 447 nuclear power reactors in operation and 52 nuclear power reactors under construction. The 126 nuclear power reactors in operation in the EU represent roughly 28 percent of the global fleet whereas the 6 nuclear power reactors under construction in the EU represent less than 12 percent of the global number of nuclear power reactors under construction. These facts indicate that the centre of gravity for the operation of nuclear and most importantly for the new projects and, thus, the future of nuclear is outside of the EU and Europe.

447 **nuclear power reactors in operation in the world**

52 **nuclear power reactors under construction in the world**

126 **nuclear power reactors in operation in the EU**

6 **nuclear power reactors under construction in the EU**

Yet, the EU with its nuclear industry, operating utilities, R&D institutions, regulatory bodies, academia, civil societies and European associations such as SNETP with its three pillars NUGENIA, ESNII and NC2I or ETSON could contribute significantly to the safe and sustainable use of nuclear energy globally. As the future European market is unclear and can be shrinking as well as growing, this outreach is crucial for the future European nuclear R&D.

This document has identified the main R&D topics with respect to reactor technology in the areas of operation and construction, in-service inspection, qualification and non-destructive examination, advanced reactors and the next generation and small modular reactors. As regards the enabling conditions the main R&D topics have been identified in the areas of safety of nuclear power plants, development of fuel, the fuel cycle and spent fuel management, dismantling and decommissioning, and social, environmental and economic aspects.

> *The EU with its nuclear industry, operating utilities, R&D institutions, regulatory bodies, academia, civil societies and European associations such as SNETP with its three pillars NUGENIA, ESNII and NC2I or ETSON could contribute significantly to the safe and sustainable use of nuclear energy globally.*

With respect to cross-cutting technologies, the main R&D topics have been identified in the areas of digitalisation, modelling and simulation, and materials and with respect to non-technological cross-cutting aspects, the main R&D topics have been identified in the areas of research infrastructures, harmonisation, and education, training and knowledge management. Being an SNETP document, the viewpoint is European and based on the needs of the SNETP member organisations. However, all of these R&D topics are relevant globally. Depending on the scale and phase of the nuclear program the importance of the individual subjects may vary.

The strength of the SNETP SRIA is the wide palette of on-going and planned R&D activities from the 'cradle to the grave', the strong and versatile R&D infrastructure including also new research facilities, and the strong education and training components. This palette offers possibilities for cooperation with the R&D of established nuclear countries for peaceful use of nuclear energy. In these cases, the best outcome is benefitting from the strengths of the partner. As regards embarking nuclear countries, the experience gained by the SNETP members, the availability of existing R&D infrastructure and programmes as well as availability of versatile education and training is a strong asset. Embarking countries may need advice and assistance in developing their own R&D framework and infrastructure.

Quite often the established small/medium nuclear countries as well as the embarking nuclear countries have strong ties to the country of origin of the reactor technology employed or planned to be employed. In these cases, the role of the SNETP research could be for instance as offering confirmatory R&D, a second opinion or complementary education and training.

The first step of the outreach can be a cooperation agreement of SNETP and/or its pillars with an international organisation or with some national R&D program. To some extent SNETP or its individual pillars have already taken this step. The next step is implementation of the cooperation. Largely, this step still awaits its realisation. The following steps consist of deepening the cooperation in a case-by-case basis.

The final step and the offspring beyond the scope of the SNETP is competitive contract work done by the European organisations for the clients from outside Europe. Considering the level of public governmental or EU funding for nuclear R&D this kind of activity is a must for the survival of the R&D organisations in many small EU countries. The material and immaterial R&D carried out according to SNETP research agenda and in cooperation with partners from other continents can act as the starting point of such an activity that finally increases the prosperity of these European organisations. This further enables these organisations to maintain their high level of competence and thereby contributes to the continued safe and sustainable use of nuclear energy in the future also in Europe.

7. CONCLUSIONS AND WAY FORWARD

Independent reputed international energy outlooks clearly indicate that the world and Europe in particular will need to include nuclear fission energy in its energy mix when it wants to fulfil its low-carbon energy generation ambitions and minimise the probable effect on climate change. SNETP is fully aligned with this conclusion. At the same time, SNETP as an organization has made an important step towards a legal association. The maturity of the organization and its pillars has allowed to update the Strategic Research and Innovation Agenda. This agenda shows that the long-term vision of SNETP is still valid, while at the same time small changes in priorities can be identified reflecting the changing landscape and progress in research and innovation methods, tools, and knowledge.

While safety will always remain a first principle in nuclear research, this update of the Strategic Research and Innovation Agenda emphasizes that research towards affordability, reliability and financial risk mitigation is a boundary condition for long-term operation and future deployment of nuclear systems. After all, without long-term operation and new nuclear deployment in Europe, we will not be able to meet the environmental goals set in international agreements. This also shows the need for proper communication channels on nuclear to inform the public at large about the benefits of nuclear energy. Together with organizations like Foratom, the OECD/NEA, and the IAEA, SNETP will continuously ensure that factual information will be provided to the public.

> ***The world and Europe in particular will need to include nuclear fission energy in its energy mix when it wants to fulfil its low-carbon energy generation ambitions and minimise the probable effect on climate change.***

The current Strategic Research and Innovation Agenda 2020 has been aligned well with the Strategic Energy Technology (SET) Key Action 10 Implementation Plan (EC, 2019), including the visions of the three SNETP pillars, NUGENIA, ESNII, and NC2I.

SNETP
Sustainable Nuclear Energy Technology Platform

NUGENIA
Nuclear Generation II&III Alliance

ESNII
European Sustainable Nuclear Industrial Initiative

NC2I
Nuclear Cogeneration Industrial Initiative

The future for development and deployment of nuclear technology in Europe is bright if we manage to:

- Operate our assets in a reliable, affordable and safe way;
- Collaborate in Europe and internationally;
- Connect scientists and reactor designers (to ensure we are working on the right challenges);
- Link experimental teams with numerical modellers (to ensure mutual knowledge exchange improving both sides of the scientific spectrum);
- Educate continuously a new European nuclear workforce;
- Communicate in an effective way the benefits of nuclear energy to the European citizens.

> ***This update of the Strategic Research and Innovation Agenda emphasizes that research towards affordability, reliability and financial risk mitigation is a boundary condition for long-term operation and future deployment of nuclear systems.***

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Obviously, future deployment of nuclear systems and nuclear research infrastructure in Europe will also strongly depend on the financial conditions and long-term political support of member states. Funding mechanisms put forward by the European Commission, e.g. through Horizon Europe, but also national initiatives will play an important role in which SNETP may act as a catalyser to encourage collaboration and maximise integration of research, development, and innovation efforts. Funding will remain a major challenge. A significant increase in funding levels will allow to cover properly all the needs identified within this Strategic Research and Innovation Agenda. This development will also depend on the deployment of renewables to which the nuclear industry will have to adapt.

> *Future deployment of nuclear systems and nuclear research infrastructure in Europe will also strongly depend on the financial conditions and long-term political support of member states.*

> *A significant increase in funding levels will allow to cover properly all the needs identified within this Strategic Research and Innovation Agenda.*

8. GLOSSARY

ADS	Accelerator Driven System
ALARA	As Low As Reasonably Achievable
ALFRED	Advanced Lead Fast Reactor European Demonstrator
ALLEGRO	GFR Demonstrator
ALLIANCE	European Radioecology Alliance Association
AMP	Ageing Management Plan
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
ATF	Accident Tolerant Fuel or Advanced Technology Fuel
CANDU	Canadian Deuterium Uranium reactor
CO_2	Carbon-dioxide
CONCERT	European Joint Programme for the Integration of Radiation Protection Research
D&D	Dismantling and Decommissioning
DBA	Design Basis Accident
DBE	Design Basis Events
DEC	Design Extension Conditions
DHR	Decay Heat Removal
EC	European Commission
EERA-JPNM	European Energy Research Alliance – Joint Program on Nuclear Materials
ENEF	European Nuclear Energy Forum
ENIQ	European Network for Inspection and Qualification
ENSREG	European Nuclear Safety REgulators Group
ESNII	European Sustainable Nuclear Industrial Initiative
EU	European Union
EUR	European Utility Requirements
EURADOS	EUropean RAdiation DOSimetry
EURAMED	EURopean Alliance for MEDical radiation protection research
GEMINI	Collaboration between NC2I and NGNP
GFR	Gas Fast Reactor
GIF	Generation IV International Forum
HTGR	High Temperature Gas-cooled Reactor
I&C	Instrumentation and Control

IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGDTP	Implementing Geological Disposal Technology Platform
IPCC	International Panel on Climate Change
ISI	In-Service Inspection
JHR	Jules Horowitz Reactor
LCOE	Levelized Costs Of Electricity
LFR	Lead Fast Reactor
LLW	Low Level radioactive Waste
LMFR	Liquid Metal Fast Reactor
LTO	Long-term Operation
LW-SMR	Light Water – Small Modular Reactor
LWR	Light Water Reactor
MCCI	Molten Core Concrete Interaction
MELODI	Multidisciplinary European LOw Dose Initiative
MINERVA	Phase 1 of the MYRRHA project
MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide
MSR	Molten Salt Reactor
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
NC2I	Nuclear Cogeneration Industrial Initiative
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
NEA	Nuclear Energy Agency
NERIS Strategies	European Nuclear and Radiological Emergency Management and Rehabilitation
NGNP	Next Generation Nuclear Plant
NI2050	Nuclear Innovation 2050
NPP	Nuclear Power Plant
NUGENIA	NUclear GENeration II & III Association
ODS	Oxide Dispersion Strengthened
OECD	Organisation for Economic Cooperation and Development
PIE	Post Irradiation Examination
PINC	Nuclear Illustrative Programme
PLiM	Plant Life Management

PWR	Pressurized Water Reactor
R&D	Research and Development
RI-ISI	Risk Informed In-Service Inspection
RPV	Reactor Pressure Vessel
SAMG	Severe Accident Management Guidelines
SAR	Safety Analysis Report
SET	Strategic Energy Technology
SFR	Sodium Fast Reactor
SMFR	Small Modular Fast Reactor
SMR	Small Modular Reactor
SNETP	Sustainable Nuclear Energy - Technology Platform
SSC	Structures, Systems, and Components
TA	Technical Area (of NUGENIA)
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
WNA	World Nuclear Association

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