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

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 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.

141 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.

- 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).

It should be remembered that nuclear facilities are designed, constructed, operated and maintained for safe and reliable operation in accordance with

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

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.**

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