ESNII VISION PAPER

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ESNII Vision Report

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Executive Summary

The Sustainable Nuclear Energy Technology Platform (SNETP) was established in 2007 as a Research & Development & Innovation (R&D&I) platform to support and promote the safe, reliable and efficient operation of civil nuclear systems. The European Sustainable Nuclear Industrial Initiative (ESNII) has been launched in 2010 under the umbrella of SNETP and is one of its 3 pillars.

The ESNII initiative has been able to gather European teams around technologies and demonstration projects to pursue R&D on Generation IV systems using technologies based on fast neutron spectrum and closed fuel cycles allowing competitive and sustainable energy production, better use of the uranium resources as well as waste minimization. The main strategy is to promote the advances in R&D&I of these technologies, strengthening synergies and utilizing common technical solutions to maximize effectiveness of the whole process.

In particular, sustainable industrial initiatives supported by the following technologies and projects are promoted within ESNII:

1. Lead-cooled Fast Reactor (LFR);
2. Gas-cooled Fast Reactor (GFR);
3. Sodium-cooled Fast Reactor (SFR);
4. Molten Salt Reactor (MSR).

The MYRRHA project, an Accelerator Driven System to demonstrate transmutation of high-level waste, was judged having potential in support to these ESNII technologies.

The present document describes the ESNII mission, vision, key areas requiring RD&I and intended actions.

1. ESNII Mission

The European Sustainable Nuclear Industrial Initiative (ESNII)[1] has been launched in 2010 under the umbrella of the Sustainable Nuclear Energy Technology Platform (SNETP)[2]. ESNII is established as one of the three pillars of SNETP.

Its mission stems from the energy needs assessment of the European economy and focuses on Generation IV systems with closed fuel cycles in line with the objectives and timing of the integrated Strategic Energy Technology Plan issued by the European Commission (SET-Plan)[3].

Other organizations worldwide pursue comparable objectives. The Generation IV International Forum (GIF)[4] was founded in 2001 and gathers research teams all around the world on comparable R&D subjects. Since it is a worldwide organization, it can gather more resources and study more systems than the ESNII technologies and projects. However, and for understandable reasons, GIF is not committed to demonstrator projects or first of a kind system like ESNII and limits its scope to technologies. ESNII representatives and in particular its industrial members participate to a GIF subgroup: the Senior Industrial Advisory Panel (SIAP). The International Atomic Energy Agency (IAEA)[5] performs long term technology evaluation exercises in its INPRO [6] section. ESNII and SNETP representatives are interacting with INPRO to present the European Generation IV approach and in particular its MOX fuel R&D strategy.

The use of fast reactors in a closed U-Pu fuel cycle (recycling of spent fuel) can increase efficiency in natural resource consumption by at least a factor of 50, enabling a more sustainable long-term implementation of nuclear energy. For Europe, this approach offers additional strategic benefits: leveraging existing spent fuel stockpiles to enhance resource sovereignty, optimizing resource utilization while reducing the burden of long-lived radioactive waste, diversifying energy production, and lowering overall energy system costs through reliable baseload and dispatchable power. Together, these advantages contribute to building a robust, affordable, and independent European energy system.

One of the societal concerns regarding nuclear energy is the high-level nuclear waste. Fast spectrum reactors with closed fuel cycles can allow a significant reduction in radiotoxicity and volume of high-level nuclear waste. Apart from the deployment of fast reactors, advanced reprocessing and remote fuel manufacturing techniques are needed to recycle the minor actinides in order to meet this goal.

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[1] ESNII: https://snetp.eu/esnii/
[2] SNETP: - www.snetp.eu
[3] SET-Plan: - https://setis.ec.europa.eu/actions-towards-implementing-integrated-set-plan
[4] GIF: https://www.gen-4.org/gif/jcms/c_9260/public
[5] IAEA: https://www.iaea.org
[6] INPRO: https://www.iaea.org/services/key-programmes/international-project-on-innovative-nuclear-reactors-and-fuel-cycles-inpro

2. ESNII vision

ESNII aims to develop safe and operational nuclear reactor technologies with closed fuel cycle Generation IV energy systems - allowing competitive and sustainable energy production, better use of the natural resources and waste minimization. The potential of these technologies for cogeneration of industrial heat is a further element to foster, considering the increased interest for other nuclear energy applications than electricity generation only (such applications being specifically addressed, inside SNETP, by the pillar NC2I.

In particular, sustainable industrial initiatives supported by the following technologies and projects are promoted within ESNII:

1. Lead-cooled Fast Reactor (LFR);
2. Gas-cooled Fast Reactor (GFR);
3. Sodium-cooled Fast Reactor (SFR);
4. Molten Salt Reactor (MSR).

In 2021, ESNII analysed the MSR technology based on fast (or even epithermal) neutron spectrum and concluded it can be currently considered as an emerging initiative of high potential in terms of sustainability. Therefore, ESNII included MSR among the technologies of interest requiring investments in basic R&D to prove feasibility and to support the definition of a reference concept and associated demonstration roadmap.

In 2024, ESNII decided to structure itself by technology in order to facilitate the achievement of its vision, that being to foster dialogue within and among the communities developing the ESNII sustainable technologies in order to define common projects towards the design of demonstrators intended to be available on the market as soon as possible, considering the expected nuclear market growth in the next decades which claims for a proper answer in terms of full cycle sustainability. Complementarity between ESNII and the SNETP-backed European initiative ‘SMR Industrial Alliance’ will be pursued.

The application of the targeted technologies is not restricted to the production of electricity (still considered as a priority by ESNII). These facilities could also serve energy needs beyond the production of electricity, as increasingly requested from the EU decarbonization targets. However, the generation of heat alone is not the target of the ESNII systems, which have the potential to increase the efficiency and the sustainability of the power generation reactor fleet.

Numerous start-ups developing the ESNII technologies are also emerging up in the recent years: ESNII will make efforts to identify and gather the needs of these start-ups, as well as to facilitate the consensus among the start-ups and other ESNII members in the different technology tracks in developing projects and assessing their market deployment potential.

3. Key areas requiring R&D&I

This section outlines several key areas requiring RD&I (Research, Development, and Innovation) before widespread sustainable nuclear power generation can be achieved:

3.1 Component development, manufacturing and qualification

ESNII technologies require the development of innovative components for competitive and safe operation, throughout the life cycle of the plant. A comprehensive range of solutions is being engineered, including core-related components, heat transfer solutions, pumping systems, confinement and containment components.

Most innovative components are safety-related, in that either they perform a direct safety function, or their failure would have a potential impact on the safety of the reactor. Nuclear design codes (in particular, RCC-MR(x) and ASME) offer a comprehensive set of design rules to ensure an adequate level of safety in materials selection, design, manufacturing, inspection and repair, as a solid basis for the licensing of the plant. However, specific features of these technologies, either due to primary coolant properties or to innovative approaches aiming to increase plant competitiveness, mean that their components are not always fully covered by existing design codes. Dedicated testing is required together with the development of procedures for qualification prior to the formulation of appropriate codes as well as with the development of new design codes applicable to the operating conditions of components in innovative nuclear plant described in Section 4.

Advanced manufacturing techniques (e.g., additive manufacturing, thermal bonding), already introduced in non-nuclear applications, are gaining increasing attention among nuclear designers to ease the prototyping process, reduce costs and increase performances of main components.

Early involvement of a qualified supply chain for the development and testing of prototypical components will allow for optimized solutions for future deployment phases. Prototyping of scaled-down components allows for preliminary assessment and validation of design principles and performances, through dedicated testing and qualification in relevant environment.

3.2 Fuel manufacturing and testing

ESNII has been concentrating its R&D effort on MOX fuel for its leading demonstrators (SFR, LFR, GFR, MYRRHA). This effort can build on the considerable experience existing in Europe in fast reactor MOX fuel. Switching to other fuels such as nitrides or carbides for the demonstrators would delay their calendar by more than 15 years and require costly R&D programmes. With the help of the European Commission – via the Euratom Programme – which has funded or co-funded several projects (ESNII+[7], ESFR_SMART [8], INSPYRE[9] , PUMMA[10] labelled by ESNII and MIMOSA[11] - competencies could be maintained in European R&D teams for measurements of physical and chemical MOX properties in the parameter regimes of the future demonstrators. This is of great importance for the future MOX fuel designs.

[7] ESNII+: https://cordis.europa.eu/project/id/605172;
[8] ESFR_SMART : https://cordis.europa.eu/project/id/605172;
[9] INSPYRE: http://www.eera-jpnm.eu/inspyre/
[10] PUMMA: http://www.nuclearenergy.polimi.it/pumma/;
[11] MIMOSA : https://cordis.europa.eu/project/id/101061142

The general ESNII R&D objectives are to increase the knowledge of UO2-PuO2 fuels at high burn up and at high PuO2 content, above 26%, which will be needed for plutonium multi-recycling in fast spectrum research reactors and demonstrators. This R&D is closely related to the cladding behaviour at high burnup, described in the materials development section.

In the context of plutonium multi-recycling in molten salt reactors, liquid fluoride and chloride fuels are studied with the aim of collecting thermophysical data as input to enveloping salt property models, including the impact of fission and corrosion products, as basis for molten salt thermal hydraulic behavior. Chemical interaction with structural materials are separately addressed in dedicated loop tests, accompanied by nuclear experiments, to confirm composition and speciation assumptions.

Material development and testing

The availability of materials resistant to neutron damage, to high temperatures and to the aggressiveness of non-moderating coolants, is a condition to deploy fast and epi-thermal reactors. Other conditions are to prepare the industrial capabilities (manufacturing and welding technics …) and to develop a suitable construction code (ESNII and AFCEN[12] collaboration is in place).

Austenitic steel is the reference structural material for SFR and LFR. The completion of this long-lasting programme is relevant for all future projects. Particular attention should be paid to deepening knowledge of thermal ageing phenomena, creep and creep-fatigue damage (necessary for component lifetime justification). Also, the use of coatings to prevent corrosion in the more aggressive coolants would have to be qualified.

The development of new candidate steels, initiated in a series of former and ongoing EU projects (e.g. INNUMAT[13] labelled by ESNII), must be continued with new fabrications, characterization and irradiation tests.

Recent development of Accident Tolerant Fuels (ATF) also boosts the development in this area. For critical parts of the reactor (active parts of heat exchangers, core support plate), refractory metallic alloys such as nickel-based alloys or innovative materials (e.g. high-entropy alloys, ceramics...) require appropriate qualification.

Qualifying new materials or new manufacturing processes can be a long process and the long lead times involved produce an effective and consequent barrier to market entry of new or optimised materials and processes at an industrial scale. It is therefore a key priority to reduce the time from development to deployment of advanced material solutions by focused long-term collaborative campaigns supported by advanced modelling techniques.

3.3 Development and validation of design and safety analysis codes

The overall success of the ESNII mission depends on, among other factors, the ability to develop, demonstrate, and deploy advanced reactor designs that exhibit excellent safety characteristics. Safety assessment must be based on appropriate methodologies (i.e., accepted by the safety authorities) and a deep knowledge of the physical phenomena and behaviour of materials. With the help of the European Commission – via the Euratom Programme – which has funded or co-funded several projects

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[12] AFCEN: https://www.afcen.com/en/

[13] INNUMAT: https://www.innumat.eu/

recently labelled by ESNII like LESTO [14] and ANSELMUS [15] for LFR, SAFeG [16] and TREASURE [17] for GFR, ESFR-SIMPLE [18] for SFR, ENDURANCE [19] or MSR, competencies could be maintained in European R&D teams in these domains.

Thermal hydraulics is recognized as one of the key topics in the design and safety analysis of fast reactors. Thermal-hydraulic challenges[20] that appear in liquid-metal-cooled fast reactors (LMFRs), with a focus on pool-type reactors, as well as in Molten Salt Reactors, can be divided in three main categories: core thermal-hydraulics, pool thermal- hydraulics, and system thermal-hydraulics. For each of these main categories, a division is made between normal reactor operation, off-normal conditions and severe accidents. The seven basic phenomena that are at the basis of the challenges mentioned above are turbulent heat transfer, thermal fluctuations, mechanical fluctuations, mass transfer, bubble transport, particle transport, and solidification. The coupling of thermal-hydraulics with neutronics is of relevance for every liquid-cooled fast reactor, as phenomena such as reactivity fluctuations caused by thermal-hydraulic variations (and vice versa) are important to consider. The safety demonstration of fast reactors relies in large part on the numerical simulation of various transients. In order to qualify these simulations, the numerical tools used must be checked for correctness (verification). Their capability to correctly predict the physics of each transient must be assessed against an exhaustive experimental database.

Code validation is a part of the overall safety assessment. For each physics, there are several simulation tools among European players. This is an asset as it allows, inter alia, benchmark exercises. In addition, dedicated experimental programs are necessary in support of design verification and code validation and uncertainty quantification. These costly realizations could be pooled between European partners and possibly with non-European players, with the help of instruments like the Euratom programme or possibly of the European Industrial Alliance on SMR's.

3.4 Testing and experimental infrastructure for design and R&D&I

The research infrastructure currently available, or under construction in Europe, contains only a few facilities able to reproduce the environments in the ESNII technologies, through dedicated test channels or experimental loops and integral facilities. A technology implementation plan for the development, testing, and qualification of prototypic elements to support design and licensing of an innovative solution requires a progression from non-nuclear out-of-pile testing through nuclear in-pile testing (where needed), and from laboratory- to full-scale.
Demonstrator reactors provide the capability for the validation of innovative technologies at high neutron fluxes and temperatures in fully prototypical conditions. As such, ESNII demonstrators of relevant size are an essential step in the deployment strategy of the technologies. Beyond validation of their respective technology, demonstrators offer in addition qualification capabilities in a representative environment. Furthermore, they offer essential capabilities for verification and validation of computational tools and nuclear data, helping to reduce associated uncertainties and strengthen confidence in future reactor performance... In terms of engineered safety features,

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[14] LESTO : https://cordis.europa.eu/project/id/101166337
[15] ANSELMUS : https://cordis.europa.eu/project/id/101061185
[16] SAFeG : https://www.safeg.eu/
[17] TREASURE : https://cordis.europa.eu/project/id/101164616
[18] ESFR-SIMPLE : https://cordis.europa.eu/project/id/101059543
[19] ENDURANCE : https://cordis.europa.eu/project/id/101165896
[20] Roelofs F. edit., 'Thermal Hydraulics Aspects of Liquid Metal Cooled Nuclear Reactors', ISBN 978-0-08-101980-1, Woodhead Publishing, Elsevier (2019).

additional design provisions to mitigate very unlikely events or sequences of events might be needed if insufficient evidence is provided to exclude such conditions.

3.5 Fuel cycle including decommissioning and backend

Closing the nuclear fuel cycle within a circular economic approach is an essential part of the choice for fast reactors so that nuclear power generation can attain the full benefit of waste minimization and resource optimization. While conventional aqueous reprocessing is a well-established method to treat LWR Spend Nuclear Fuel (SNF), the use of aqueous solutions limits the activity of the fast reactor SNF to be treated due to radiolysis. Although the applicability of the method could be of interest for MSRs operating in a closed fuel cycle strategy, alternative procedures are required, especially to treat high-burnup fuel from all of the ESNII technologies.

Pyro processing is a non-aqueous technology to purify SNF applying various (electro)chemical separation steps in high-temperature molten salts. The technique allows processing of short-cooled SNF with an intense radiation level due to the inherent radiolysis resistance. This enables fuel cycles of acceptable (limited) lifetimes. In addition, pyro processing holds important potential advantages compared to an aqueous reprocessing methodology such as producing highly proliferation resistant (actinide) product streams, producing less radioactive waste and requiring small footprint installations allowing on-site reprocessing. Performance of the investigated processes has to be based on economic aspects, safeguarding, final waste storage compatibility and installation footprint. The connection of pyro processing and molten salt reactors could be considered, as it could offer opportunity of enhancing the economics of fuel cycle closure

3.6 Cross-cutting technologies (e.g. Digitalisation)

The continuous progress in digital technology creates more and more powerful tools like advanced simulation, virtual imaging, augmented reality and artificial intelligence. For modelling and simulations, the general trend includes developments and validation of multi-scale, multi-physics and multi-phase analysis tools as well as uncertainty quantification methodologies. Integrated applications include the development of digital twins of nuclear reactors, that are able to simulate realistic situations throughout a plant's lifetime, from design to decommissioning. These advances can be utilised to increase the safety and efficiency of activities in the nuclear domain from data gathering and analysis, through design, operation and maintenance to recycling and decommissioning.
Increasing development and use of artificial intelligence through for example machine learning techniques will speed up progress in the above fields.

3.7 Coolant chemistry

A R&D&I programme for coolant chemistry control includes four main topics:

- The chemical interaction of the coolant with structural materials, as coolant chemistry affects the interaction with structural materials and vice-versa.
- The control of the coolant itself includes the mastering of the coolant condition as well as the management of impurities. Specific sensors and control methods as well as filter systems have to be developed for these purposes and tested in dedicated pilot-scale loops.
- The measurement of the transport of radioactive elements in the coolant, in both normal operation, transient and accident conditions. Phase change mass transfer as well as aerosols have to be considered. Also, capture systems for volatile radioactive elements need to be developed. The results of these studies are used as input for safety analyses.
- Component cleaning and decontamination. This is a relevant information for the reactor maintenance programme and the decommissioning plan.

3.8 Instrumentation

The instrumentation needed for the safe and reliable operation of the ESNII reactors will enable continuous monitoring of operating parameters like temperature, flow rate, neutron flux etc., as well as the indicators of the state of the structures and components such as mechanical deformations, the presence of leaks and cracks etc. The instrumentation has also to be able to provide, mostly in a diversified manner, the necessary measurements in order to detect or possibly forecast the identified panel of incidents and potential hazards resulting from the safety studies. Periodic inspection programmes must validate the hypothesis and project values concerning the damaging mechanisms considered during the design studies. A specific category of instrumentation is therefore needed for the inspection of structures and components as well as for the assistance in possible repair, cleaning, cutting etc.

3.9 Fuel Handling systems

Fuel handling systems are key for the operability of reactors and the attainment of competitive availability factors. The Generation IV systems supported by ESNII seek to master the specificities of these systems, strongly different if compared to Generation III concepts. ESNII systems motivate R&D efforts and technological development requiring experimental facilities covering the main topics of interest as: the tribology of mechanical systems and their whole reliability under specific environment, remote operation and robotics applications with the whole enhancement of the safety and reliability of these systems. Stakes dealing with the spent fuel decontamination processes (i.e., cooling fluid residues elimination) and storage are specifically addressed, taking into account the fuel cycle next steps requirements. Innovation is driven by the simplification of the handling systems, their reliability and performances (automation) with the objective to contribute to the industrial relevance of the Generation IV concepts considered.

3.10 Harmonization of safety standards.

In relation with Technical Support Organisations (TSOs), the Risk and Safety Working Group of the Generation IV International Forum has produced technology-neutral guideline reports and recommendations[21.] It contributes to the harmonization of methods and safety standards, which is of primary importance for the future of nuclear industry. Applying these methodologies to ESNII technologies and projects is useful in preparation of the licensing process, to get a consensus among the different actors. The recent EU-funded HARMONISE[22] project including ESNII members intends to formulate a comprehensive approach in order to acquire the knowledge needed for the harmonisation and standardisation of methodologies, codes and standards as well as the assessment of nuclear reactor components. The project will tackle issues related to qualification, standardisation, verification & validation, as well as licensing of fission and fusion installations

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[21] https://www.gen-4.org/gif/jcms/c_40424/risk-safety-working-group-rswg

[22] HARMONISE : https://cordis.europa.eu/project/id/101061643

4. ESNII Actions

In order to realise its goals, ESNII firmly aims, in synergy with other SNETP pillars:

- To share a common technological roadmap and to develop synergies among national and EU-funded programs, based on sustainable industrial initiatives.
- To promote and support the research and demonstration programmes needed to implement this roadmap, when the hereunder condition will be fulfilled for construction decision:
    - Availability of the necessary R&D results for design options selection,
    - Relevance for future utilities' needs,
    - Positive feedback from licensing authorities.
- To consolidate the technology roadmap and to promote the construction of the research and testing facilities that are necessary for the demonstration programmes leveraging on the synergies with other research initiatives included in ESFRI (*European Strategy Forum on Research Infrastructures*[23]) and taking into account the ERA (*European Research Area*[24]) vision.
- To establish the common basis of an R&D, industrial and financial partnership, facilitating the constitution of consortia and private-public partnerships for the best exploitation of the developed technologies and projects.
- To provide indications on the design, safety and operational criteria under which the assessment of the identified technological options as well as various complementary and emerging technologies shall be made to establish a sound and timely process for the evaluation of the technologies, the associated projects and their potential.

[23] ESFRI: https://www.esfri.eu/

[24] ERA: https://ec.europa.eu/info/research-and-innovation/strategy/era

5. Abbreviations

AFCEN	Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électronucléaires
ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator
ATF	Accident Tolerant Fuels
ERA	European Research Area
ESFR-SMART	European Sodium Fast Reactor Safety Measures Assessment and Research Tools
ESFRI	European Strategy Forum on Research Infrastructures
ESNII	European Sustainable Nuclear Industrial Initiative
ETIP	European Technology and Innovation Platform (by the European Commission)
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
LFRIAEA	International Atomic Energy Agency
INPA	international non-profit association (under the Belgian law pursuing networking and scientific goals).
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INSPYRE	INvestigations Supporting MOX fuel licensing in ESNII PrototYpe REactors
LFR	Lead-cooled Fast Reactor
MOX	Mixed OXides
MSR	Molten Salt Reactor
MYRRHA	Multi-Purpose hYbrid Research Reactor for High-tech Applications
ODS	Oxide Dispersion-Strengthened
PUMMA	PlUtonium Management for More Agility
R&D&I	Research and Development and Innovation
RF	Russian Federation
SET-Plan	Strategic Energy Technology Plan (issued by the European Commission)
SFR	Sodium-cooled Fast Reactor
SIAP	Senior Industrial Advisory Panel (GIF subgroup)
SMR	Small Modular Reactor
SNETP	Sustainable Nuclear Energy Technology Platform
TSO	Technical Support Organization

ESNII
European Sustainable
Nuclear Industrial Initiative

ABOUT ESNII

The **European Sustainable Nuclear Industrial Initiative (ESNII)** addresses the need for demonstration of Generation IV Fast Neutron Reactor technologies, together with supporting research infrastructures, fuel facilities and R&D work.

ESNII is one of the three pillars of the Sustainable Nuclear Energy Technology Platform (SNETP) that was established in September 2007 as a R&D&I platform to support technological development for enhancing safe and competitive nuclear fission in a climate-neutral and sustainable energy mix. Since May 2019, SNETP has been operating as an international non-profit association (INPA) under the Belgian law pursuing 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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