Organisation of the European Research Community on Nuclear Materials

A Coordination and Support Action in Preparation of a Co-Funded European Partnership on Nuclear Materials

This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997

ORIENT-NM vision on nuclear materials research for all reactor generations

March 2022

Executive summary

ORIENT-NM is a Euratom-funded coordination and support action with the objective of exploring the opportunity of setting up a European partnership on nuclear materials, establishing the relevant Strategic Research Agenda, governing structure and interaction with stake-holders.

The analysis of the national energy and climate plans (NECP) reveals that, by 2040, a significant number of EU member states intend to maintain or even expand their nuclear installed power through LTO, power uprates and new builds. In addition, game-changers such as small modular reactors and advanced designs of interest throughout the continent may lead nuclear energy to be even more widespread in 2040 than currently foreseeable. Recent dramatic geopolitical events might also have an impact on this.

Research to understand materials behaviour and improve materials properties plays a crucial role to enhance safety, efficiency and economy of nuclear energy. The materials involved range from concrete and metallic structural alloys, to polymers, fuel and also substances for neutron control. Accurate health monitoring of these materials while operating is also needed. To enable progress towards enhanced safety, efficiency and economy of nuclear energy, the development, manufacturing and qualification of innovative nuclear materials must be accelerated, thus reducing their time to market. This implies a shift from the traditional "observe and qualify" to the modern "design and control" materials science approach. Advanced digital techniques and suitable models are the enablers of this shift.

This paradigm shift in nuclear materials science is at reach for Europe provided that an integrated nuclear materials research programme, i.e. a partnership, is set up to make coordinated use of assets that are spread across member states and associated countries. The partnership will need and feed available schemes and roadmaps for access to, and use of, infrastructures, such as those designed in the parallel coordination and support action JHOP2040 for utilising Euratom access rights in the Jules Horowitz Reactor, or established in the framework of international organisations (e.g. OECD/NEA's FIDES framework).

Such integrated nuclear materials research programme, consistently with the activities foreseen in the SET-plan implementation plan on nuclear safety, will pivot around five research lines that are transversal through all classes of nuclear materials, namely: (1) nuclear materials test-beds, (2) nuclear materials acceleration platforms, (3) combined physics-based and data-driven models, (4) advanced materials and component health monitoring and (5) European nuclear materials FAIR database. Such transversal programme is expected to leverage substantial national and industrial support. Because of its transversal nature, it will maintain and build competences and will equally serve all the various nuclear energy national strategies, supporting nuclear industry competitiveness and robust supply chain, with benefits for fusion and non-nuclear energy, as well.

Table of Contents

1. Introduction

ORIENT-NM (Organisation of the European Research Community on Nuclear Materials) is a Coordination and Support Action (CSA) partially funded by the Euratom research and training work-programme 2019-2020, which was set up, consistently with the call request, to explore the opportunity of establishing a European partnership on nuclear materials, following a procedure already adopted in the past for other currently existing partnerships, e.g., EURAD. This document presents the vision of the European research community on nuclear materials, as represented in ORIENT-NM, regarding:

- The role of current and future nuclear systems as crucial components, together with renewables, of a resilient and sustainable Energy Union, helping Europe to abate the use of fossil fuels, reduce European geopolitical dependence and become the first climate neutral continent by 2050 [1].
- The crucial role of materials research to enhance safety, efficiency and economy of nuclear energy, supporting the existing fleet, the new builds and also enabling the deployment of advanced reactor concepts, including small modular reactors, within the time horizon of 2040.
- The five Grand Goals that the nuclear materials research community should work towards, along corresponding research lines.

These five research lines stem from the analysis of the European member states' energy plans and of the short and long term needs of the nuclear industry. They concern acceleration of development of innovative materials solutions and their qualification, while also accounting for circularity and sustainability principles. For this, it is crucial to shift from an "observe and qualify" approach towards a more advanced "design and control" one, using advanced materials science practices combined with modern digital techniques.

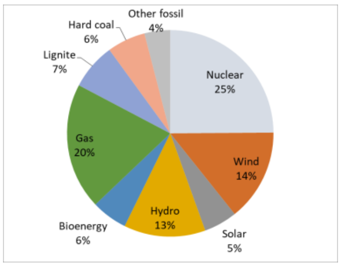
The five Grand Goals, unattainable for any single country, call intrinsically for Europe-wide collaboration. They are thought to serve equally well different nuclear energy strategies and policies, so as to be shared between all involved member states and associated countries, allowing their needs to be met, by valorising their research and industrial assets. The partnership is the tool to enable the integration and coordination of the European nuclear materials research programme around the shared Grand Goals, making optimal use of national competences, facilities and (present and future) infrastructures.

2. Nuclear energy's important role for a net zero Europe

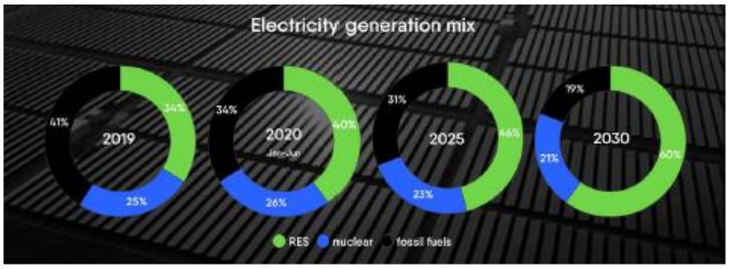
2.1 Nuclear energy contribution to decarbonisation in Europe

The transition from current fossil fuel based energy systems to low greenhouse gas (GHG) emitting ones is the core of the European Green Deal [1] and a major global challenge to face the climate change emergency. Reducing the dependence on fossil fuels has currently also important geopolitical implications.

Figure 1 shows that, despite varying national positions in Europe, different studies agree on the fact that nuclear energy remains the single largest low greenhouse gases (GHG) emitting energy source for electricity production on the continent and will maintain this role in the foreseeable future. The analysis of the National Energy and Climate Plans (NECP) [2], prepared in 2019 and revised in 2020 by each EU country, consistently reveals that, up to at least 2040, and likely also beyond, nuclear will represent a significant fraction of the electricity production in Europe [3].



Source: Eurostat (2020)



Source: Eurelectric Power Barometer (2020)

Figure 1 *- Left: Electricity generation by fuel in the EU 27, in 2020 [4]. Right: Predicted evolution of the electricity generation by fuel [5].*

This is mainly realized through long-term operation (LTO) of current light water reactors (LWR), i.e. pro-active lifetime extension beyond original design lifetime, as well as power uprates. LTO is already an established reality in all nuclear countries, including some that are planning to phase out. New-builds of evolutionary LWR designs, referred to as Generation III or III+, will also contribute to keep the nuclear electricity production stable. This will help enable the European Union to deliver on the commitments of the Paris Agreement and the 2030 Agenda for Sustainable Development [6,7].

In this context, small and medium sized modular reactors (SMR) are expected to be game-changers [8,9,10]. They will reduce significantly the initial capital costs and the time of construction, thanks to modularized production, while displaying enhanced safety performance through inherent and passive safety features. Interest for SMRs is accordingly widespread in Europe, including currently non-nuclear countries [3].

The attractiveness of SMR and the overall re-thinking of the role of nuclear energy in fighting climate change and securing energy supply may lead nuclear energy to be more widespread than currently foreseeable in 2040.

2.2 Nuclear energy's assets

Nuclear energy has predictable and relatively low prices, as reported in comparative studies [8,11], and guarantees secure energy supply, creating little if any geopolitical dependence. This is explicitly stated and explained in several NECPs that include nuclear energy in the secure energy supply section, recognising that the de-carbonisation targets could not be reached without the nuclear contribution during the transition. This is also reflected in the European Commission revision of the taxonomy for sustainable financing [12]. Base-load is also a stabilizing factor for the grid operator in an energy mix with an increasing share of intermittent renewable sources. Finally, nuclear power has demonstrated ability and high potential to provide also low GHG district heating and high temperature heat for various industrial applications, including hydrogen production and see-water desalination, which need to be duly exploited.

The alliance between renewables and nuclear energy has been shown to be the most effective response to the challenge of de-carbonisation of the energy sector [13]. Consistently, the 2018 "1.5°C-report" of the International Panel on Climate Change (IPCC) [14] points to electricity from nuclear power as key to limit global warming to 1.5°C. Nuclear energy is therefore an asset for Europe with a view to honouring the engagement to reduce GHG emissions by 55% by 2030 and towards complete de-carbonisation in 2050.

2.3 The journey towards increasing nuclear sustainability

Five issues still hamper the full-hearted adoption of nuclear as low carbon sustainable energy source in Europe: the safety of operation and the severe accident risk; the management of long-lived radioactive nuclear waste; the limited availability of fuel resources; the large initial investments, back-end costs and long construction times; and the possible misuse of fissile materials.

Continuous improvements in operational practices of current reactors, also in the context of an increased flexibility of the network, provide margins to further increase nuclear energy performance, efficiency and safety. through widespread adoption of SMR, including high temperature systems to contribute to low-GHG heat production. Crucial is that knowledge and expertise be preserved and transferred to young generations of researchers and operators, in an effort to retain and expand competences.

the overall sustainability of nuclear energy can be further increased through the commissioning and deployment of fast neutron reactors [15] combined with fuel recycling facilities. By producing more fissile material than they consume, they significantly improve the utilization of natural resources. This strongly reduces the need of mining and guarantees stable and secure energy supply, without geopolitical dependence. These systems also enable the long-term radiotoxic impact of irradiated nuclear fuel to be abated, by drastically reducing the quantity of waste and its radiotoxicity duration, especially when minor actinides are burnt in reactors or dedicated facilities. These advanced design reactors should additionally enable higher safety standards by relying on passive systems, i.e., systems that are activated by physical laws, without any need for external intervention. Finally, they will improve economy through higher energy efficiency (higher operation temperature) and the adoption of advanced SMR concepts. In order for Europe to be able to profit of these options, a cohesive and properly supported European strategy including research, innovation and knowledge management is needed. Fusion will represent a further step towards nuclear energy full sustainability, via complete elimination of high activity waste.

3. Materials crucial role for both current and future nuclear reactor systems

Materials crosscut the entire technology portfolio, from energy generation and storage to delivery and end use. Materials discovery and development are the foundation of every energy innovation: advanced batteries and fuel cells, solar panels, thermal storage systems, capture and use of CO_2. New or improved materials constitute one of the cornerstones for the global transition to a low-carbon future. This is also true for nuclear energy.

3.1 A large number and variety of nuclear materials

A nuclear reactor comprises a large number of materials [16], the properties of which are essential for its safe operation, efficiency and performance. The number of different nuclear materials is all the greater given the large variety of nuclear system designs, from current generation fission reactors to GenIV and fusion. The various classes of nuclear materials considered and targeted in this document and their inherent variety are illustrated in

Figure ***2***.

Concrete	**Metallic alloys for structural components**	**Refractory materials for structural components**	**Polymers for cables and structural applications**	**Fuel cladding materials**	**Nuclear fuel materials (fissile and fertile)**	**Materials for neutron control: absorbers, moderators, reflectors**
Type II Portland cement Chemical or mineral admixtures Shielding aggregates Reinforcing and tensioning Low-carbon …	**Customary:** Low-alloy steels Austenitic steels Zr alloys Ni-base alloys F/M steels **Prospective:** AFA steels FeCrAl ODS steels CC alloys …	Refractory metals' alloys: Mo, Nb, Ta, V, W, … Ceramic composites (SiC/SiC) Graphite …	Polyethilene: polyvinyl chloride (PVC), ethylene-propylene elastomers (EPR, EPDM), cross-linked polyethilene (XLPE), chlorosulfinated polyethilene (CSPE, Hypalon rubber); ethylene vinyl acetate, …	**Customary:** Zr alloys Austenitic steels F/M steels **Prospective:** AFA steels FeCrAl ODS steels CC alloys SiC/SiC **Coatings**: metallic, ceramics, multilayer, …	UO_2 (pellets in clad, TRISO, …) MOX Carbides Nitrides Metallic Minor actinides Thorium …	AgInCd B_4C Gd or Er or Eu oxides, Zr borides, other B compounds, …

***Figure 2** – Classes of nuclear materials considered here and their variety.*

3.2 Nuclear materials requirements

All components in a nuclear installation need to fulfil their structural and functional properties under both normal and off-normal conditions all along their design lifetime. They must in particular ensure a high degree of reliability according to specific nuclear standards and regulations, hence the importance of the involvement of standardization bodies and regulators in materials development. The materials of many of these components, especially those in the reactor core, are exposed to demanding environmental conditions in terms of neutron irradiation, temperature gradients, and corrosion under different forms, which all need to be harnessed. Materials need accordingly to be suitably selected by designers at early stages of reactor conception, based on the complete knowledge of the as-fabricated properties, the expected functionality and the operating requirements. Appropriate control, monitoring, maintenance, replacement and repair strategies are then needed to control evolution and ageing mechanisms, to ensure that the equipment is able to perform its function reliably and safely throughout its time of use.

Initial Material Properties

For most materials currently in use in nuclear facilities, design property data are available, within scatter and heterogeneities. Manufacturing processes, including welding, thermal and mechanical treatments and coatings affect significantly the materials' properties and need to be accounted for upon selection. Thus, new fabrication processes require studies to ensure compliance with regulatory requirements.
For the deployment of Gen IV reactors, with more demanding requirements on materials in terms of exposure to irradiation and high temperature, in contact with non-aqueous fluids, gaps still remain: not all relevant initial properties are available for known materials and materials with improved initial properties and resistant to severe degradation processes are needed

Ageing and Degradation Mechanisms

All ageing and/or degradation mechanisms that could be active during the required lifetime of components need to be properly understood, modelled and adequately taken into account from design through integrity assessments under all operational conditions. Material property measurements and degradation analyses through health monitoring using non-destructive examination and testing (NDE&T), coupled with diagnostics, enable accurate and continuous control of the performance of components, together with suitable preventive measures, repair technologies and replacement strategies.

Thus, in-depth knowledge of the properties of a large number and variety of materials, many still to be developed, and their evolution for their entire service life, is needed. Furthermore, new materials solutions need to include considerations of overall sustainability in terms of materials criticality, lifetime optimization and waste reduction. Finally, issues such as industrial production scalability, supply chain and standardisation are equally crucial to enable the deployment of a given materials solution on the path towards innovation.

3.3 Materials needs for Gen III/III+ reactors

The above challenges need to be met in the short term for currently operating (Gen II/III) reactors and Gen III/III+ new builds.

Materials for Gen III/III+ are selected based on long-standing experience from the operation of Gen II reactors since the 1970s and 1980s. Designs have been optimised to take into account the properties of the materials under various operational conditions. Several issues, however, have been revealed recently in connection with obsolescence and repair needs. These issues affect not only core components that have been for long the focus of research for safety reasons, but also materials such as concrete and cable polymers, the degradation of which, in an LTO framework, is a point of attention. These issues need to be examined thoroughly to ensure the necessary reliability of the components concerned and their compliance with up-to-date codes and standards. Increased efficiency of new builds and reduced costs of maintenance and availability of supply chain are expected from improved materials and new fabrication methods, which also enable the modification of component design for better performance. This approach will also benefit LTO of operating reactors, allowing the introduction of new materials or materials manufacturing. It may also facilitate the design of SMRs, particularly their modular construction in factories.

On the fuel side, new materials solutions will further improve safety margins in operational conditions, reducing reactivity and mechanical/chemical pellet-to-cladding interaction. Fuel elements with enhanced accident tolerance will also increase the time between departure from normal operation and the moment at which significant loss of geometry of the fuel assemblies occurs and the severe accident starts, and mitigate the consequence of an accident. Solutions to extend the recycling of used fuels in current reactors are also investigated.

These aspects are extensively addressed in the Sustainable Nuclear Energy Technology Platform (SNETP) Strategic Research and Innovation Agenda 2021 [17].

3.4 Materials needs for Gen IV reactors

In next generation reactors, structural and fuel materials will be exposed to significantly higher temperatures and temperature gradients, as well as increased levels of irradiation, compared to today's LWRs, as is illustrated in Figure 3 for cladding materials. Materials used in these reactors also need to be compatible with unconventional coolants, such as liquid metals, molten salts or gases, which have a high corrosive and erosive potential and for which in-service feedback experience is limited.

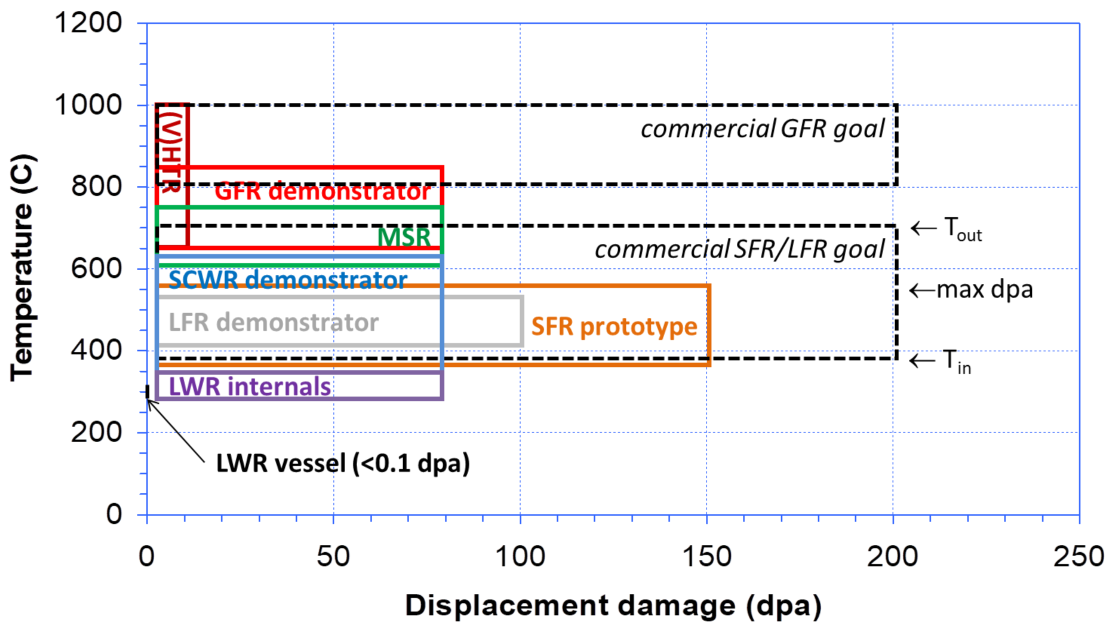


Figure 3 *– Ranges of temperature (inlet/outlet) and maximum neutron dose in the cladding in Gen IV reactor demonstrators and prototypes versus LWR, according to current EU designs. Indicative possible target regimes for commercial reactors are also indicated. From [18].*

To date, no commercial materials enable the ambitious targets of Gen IV reactor operating conditions to be fully attained. There is therefore a clear need to develop and qualify materials with suitable properties. The grand challenges for the development and qualification of materials for next generation reactors are:

- Elaboration of design rules, assessment and test procedures, for both operating and off-normal conditions, for all the materials of interest;
- Development of physical models coupled to advanced microstructural characterization to achieve high-level understanding and predictive capability, in combination with suitable data-driven modelling approaches;
- Development of advanced structural, fuel and other core materials solutions and application of advanced manufacturing techniques to achieve superior thermo-mechanical properties, better radiation-resistance and compatibility with fluids;
- Development of materials health monitoring through NDE&T methods applicable at all stages of product lifetime.

The first three challenges for metallic and ceramic structural and fuel materials are amply discussed in the Strategic Research Agenda of the Joint Programme on Nuclear Materials of the European Energy Research Alliance (EERA-JPNM) [19]. Importantly, materials with superior properties in terms of radiation and thermal gradient resistance are also crucial for fusion [20].

4. Answering Europe's materials needs for the development of nuclear systems

The above considerations show unambiguously that materials are crucial both to enhance safety and overall sustainability of current reactors and to enable the commissioning and deployment of next generation reactors, as well as fusion. The nuclear materials science community in Europe is therefore called to provide the tools, knowledge and skills to enable each European country to maintain the wished and needed nuclear capacity and/or, depending on national policies and interests, to develop advanced nuclear systems, i.e., to:

- ensure safe and affordable LTO of current generation reactors;
- design, license and construct Gen III+ new builds;
- deploy light water SMRs within the next decade;
- facilitate and reduce the time and costs for design, licensing and construction of competitive next generation nuclear reactors, including advanced SMRs within the time horizon of 2040.

4.1 Five Grand Goals of the European nuclear materials research

Addressing the challenges described above requires the application of modern materials science approaches to accelerate materials development and qualification pace. This implies shifting from an "observe and qualify" approach towards a more advanced "design and control" one, combining applied research with more fundamental approaches. The knowledge of materials' behaviour in operation will be improved thanks to models that underpin empirical performance correlations, which will enable them to be extended reliably to yet unexplored operational regimes.

Five materials science practices and relevant research lines underlie these endeavours and constitute the Grand Goals to be pursued within the next decade, for full application also beyondthis timeframe[1]:

a) Establishment of an integrated European system for the efficient application of advanced and suitably standardized experimental procedures and methodologies for nuclear materials characterization, testing and qualification, be they destructive, non-destructive or microstructural; i.e., **nuclear materials test-beds**;
b) Development of methodologies for accelerated, targeted and systematic nuclear materials improvement, or even discovery, including the whole range of variables of relevance; i.e., nuclear materials acceleration platforms, **nuclear MAPs**, which promise to be key to reduce time to market of innovation [21];

[1] These Grand Goals are consistent with, and contribute to, the research and innovation activities 1, 2, 7, 8 and 9 of the SETplan implementation plan on nuclear safety (action nr. 10, https://setis.ec.europa.eu/implementing-actions/nuclear-safety_en) and support the key enabling condition 5.

c) Development of advanced **combined physical and data-driven models** as predictive methodologies of direct application for industrial needs;
d) Development of advanced methods for **materials and component health monitoring** through non-destructive examination and testing, coupled with diagnostics and simulation tools, to enable the widespread implementation of digital twins;
e) Establishment and use of efficient platforms and procedures for data collection, storage and management (**European nuclear materials FAIR database**).

Nuclear materials test-beds and nuclear MAPs inherently require coordinated use of (present and future) European assets and facilities and exploitation of available schemes and roadmaps for access to, and use of, major infrastructures (essentially materials testing reactors and ion irradiation facilities), including those designed in the parallel coordination and support action JHOP2040 [22], or established in the framework of international organisations (e.g. OECD/NEA's FIDES framework [23]), with an eye to the possibilities offered by research facilities that will become available in the next decade (JHR, MYRRHA, PALLAS, IFMIF-DONES). In turn, these European facilities and infrastructure plans require coordination with the materials research community, especially in identifying and prioritizing the future experimental needs for material studies.

The above five research lines are transversal through all materials classes and varieties shown in Figure 2, irrespective of the specific nuclear application, and need to be combined with the opportunities offered by modern digital techniques, such as: artificial intelligence, blockchain, 3D visualisation, data analytics, high performance computing, robotics, etc. Together, these approaches and tools allow more efficient plant life and safety management, as well as better use of resources and thus improved competitiveness of the nuclear sector.

4.2 Creating an organized European research community on nuclear materials

The ambitious effort sketched in the previous section can only be achieved by promoting close, structured and continued collaboration between academia, research organizations and industrial partners all over Europe. This will enable the European nuclear materials research community to maximize the effect of the assets and financial resources that are available in Europe, avoiding duplication and fragmentation and achieving self-sufficiency. Such structured collaboration is expected to provide orientation, prioritization and continuity to the five above R&D&I lines, leveraging significant national and industrial support.

A large number of EU member states need to share the above goals, which will inherently allow each of them to valorise own research assets, in terms of knowledge and skills, as well as facilities and infrastructures, irrespective of their specific interests as to current and/or future nuclear systems. This is in fact the bottom-line of the identification of the transversal Grand Goals sketched in the previous section. This coordinated use of resources, in the specific area of materials, will serve equally well different nuclear energy strategies and policies, from current to next generation, from fission to fusion.

Importantly, even though the final application determines the specific requirements that the materials need to meet, the properties of interest, and the conditions under which these properties need to be tested, it remains true that the methodology presented above is general and goes beyond nuclear applications. Nuclear materials belong to the much wider class of materials operating under extreme conditions. Therefore, even countries that do not adopt nuclear energy or are phasing out can find an interest in participating to develop materials science tools dedicated to advanced materials discovery, development, screening, qualification and monitoring, of application to other high efficiency low carbon energy technologies where materials are exposed to harsh operating environments.

The instrument to realize the above purposes is a European partnership on nuclear materials built around the above Grand Goals. The whole framework and the steps to be taken to reach the Grand Goals of the partnership will be detailed in the Strategic Research Agenda that is being worked on within the ORIENT-NM project [18], while the structure of the partnership, its way of working, its interaction with stake-holders and the opportunities offered by present and future large infrastructures in Europe will be analysed in separate dedicated documents.

References

1 https://ec.europa.eu/clima/policies/eu-climate-action_en

2 https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

3 Deliverable D1.3, "Summary of national programmes on nuclear materials", ORIENT-NM project, in preparation.

4 Eurostat electricity production in the EU: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview#Electricity_generation

5 https://snetp.eu/wp-content/uploads/2020/11/unlocking_the_potential_of_small_modular_reactors_in_the_eu-2020-030-0674-01-e-h-D003BB17.pdf

6 https://unece.org/climate-change/press/international-climate-objectives-will-not-be-met-if-nuclear-power-excluded

7 World Energy Outlook Special Report 2013, International Energy Agency, Paris

8 https://www.oecd-nea.org/upload/docs/application/pdf/2021-03/7560_smr_report.pdf

9 https://www.iaea.org/topics/small-modular-reactors

10 https://aris.iaea.org/Publications/SMR_Book_2020.pdf

11 Deliverable D10.2 - RS2b "Final report on sustainability assessment of advanced electricity supply options", NEEDS project. http://www.needs-project.org/docs/NEEDS_RS2b_D10-2%20-%20Final%20Report.pdf

12 https://ec.europa.eu/commission/presscorner/detail/en/ip_22_711

13 A bright future, Joshua S. Goldstein and Staffan A. Qvist, ISBN: 978-1-5417-2410-5, NY: Public Affairs, 2019

14 IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]., https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf

15 https://www.gen-4.org/gif/

16 Tulenko, J.S. Nuclear Reactor Materials and Fuels. In: Nuclear Energy, Nicholas Tsoulfanidis Ed., Springer, New York, NY (2013)

17 https://snetp.eu/wp-content/uploads/2021/09/SRIA-SNETP-1.pdf

18 Malerba, L.; *et al*. Materials for Sustainable Nuclear Energy: A European Strategic Research and Innovation Agenda for All Reactor Generations. Energies 2022, 15, 1845. https://doi.org/10.3390/en15051845

19 Malerba, L.; Bertolus, M; Nilsson, K.-F. Materials for sustainable nuclear energy. www.eera-jpnm.eu

20 https://www.euro-fusion.org/fileadmin/user_upload/EUROfusion/Documents/2018_Research_roadmap_long_version_01.pdf

21 Flores-Leonar, M. M.; *et al.* Materials Acceleration Platforms: On the way to autonomous experimentation. Current Opinion in Green and Sustainable Chemistry 25, 100370 (2020), https://doi.org/10.1016/j.cogsc.2020.100370

22 www.jhop2040-h2020.eu; GA nr. 899360

23 www.oecd-nea.org/jcms/pl_15313/framework-for-irradiation-experiments-fides

This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997