SNETP
SUSTAINABLE NUCLEAR ENERGY TECHNOLOGY PLATFORM

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Report on potential synergies with other technology areas

Authors: Antoine MONNET (LGI), Gilles QUENEHERVE (LGI)

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Summary

The Task 3.3 of the SPRINT project aims at an identification and qualification of potential synergies between SNETP and other technology roadmaps. This deliverable provides a list of the most relevant identified opportunities for synergies .

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Acronyms

(B)2DS	(Bellow) 2-Degree Scenario (International Energy Agency's energy mix scenarios)
(V)HTR	(Very) High-Temperature Reactor
API	Application Programming Interface
COP21	21st Conference of Parties (United Nation Climate Change Conference)
CRM	Critical Raw Material
EC	European Commission
EERA JP	European Energy Research Alliance Joint Programmes
EIT	European Institute of Innovation & Technology
ESNII	European Sustainable Nuclear Industrial Initiative
ETP	European Technology Platform
HOF	Human Organisational Factors
IAEA	International Atomic Energy Agency
ICT	Image Constraint Token
JPNM	EERA Joint Programme on Nuclear Materials
KIC	Knowledge and Innovation Communities
NC2I	Nuclear Cogeneration Industrial Initiative
NEA	Nuclear Energy Agency
NPP	Nuclea Powerplant
OECD	Organisation for Economic Co-operation and Development
PGM	Platinum Group Metals
PHES	Pump Hydroelectric Energy Storage
PWR	Pressurised Water Reactor
REE	Rare Earth Elements
SDK	Software Development Kit
SET-Plan	Strategic Energy Technology Plan
SISI	System in Service Inspection
SNETP	Sustainable Nuclear Energy Technology Platform
SRIA	Strategic Research & Innovation Agenda
WEC/TEC	Wave/Tidal Energy Converters

1 Introduction

1.1 Context

The Sustainable Nuclear Energy Technology Platform (SNETP) was officially launched in September 2007 under the auspices of the European Commission (EC), in particular DG Research and DG Energy. It is today the only European Technology Platform (ETP) recognised by the EC in the nuclear sector.

In order to preserve and strengthen the European technological leadership, SNETP aims at structuring the long-term research in nuclear at the European level, gathering diverse stakeholders such as universities, research centres, technical support organisations, industries. The scope of the platform is comprehensive, covering the whole fuel cycle and reactor systems of Generation II, III and IV types (SNETP 2007).

According to the vision of SNETP, an affordable and secure energy supply with minimized environmental impact is a prerequisite to the achievement of sustainable prosperity. Yet, the bulk of the global energy demand is currently covered by fossil fuels. To avoid negative economic impacts provoked by the volatility of energy prices and to reduce greenhouse-gas emissions, SNETP believes that the solution lies in the replacement of fossil fuels by a balanced mix of different low-carbon energy sources. In signing the COP21 Paris Agreement, decision-makers have paved the way for this more sustainable future.

Nuclear fission has proved to be a reliable source of energy for decades providing a very significant share of low-carbon electricity supply in Europe. With the willingness to maintain this share in Europe, SNETP opted to build around three pillars:

- The Nuclear Generation II & III Association, which aims to ensure the safe and reliable functioning of the current fleet;
- The European Sustainable Industrial Initiative (ESNII), which facilitates the demonstration of Gen-IV Fast Neutron Reactor technologies;
- The Nuclear Cogeneration Industrial Initiative (NC2I), aiming to explore cogeneration and non-electric applications of nuclear (SNETP 2012).

To implement these objectives into concrete actions, SNETP drafted strategic and roadmapping documents such as for instance, the Strategic Research and Innovation Agenda (SRIA). The first version was issued in 2009 and a first update in 2013. The SNETP Governing Board, in its 20th meeting in September 2017, decided to update it to reflect the changes that intervened throughout the last five years in the nuclear R&D landscape.

With this regard, the H2020 SPRINT project (2015-2019) could bring an added value to this updating process of the SNETP SRIA. One of the essential purposes of the project is indeed to support SNETP in the elaboration, wide adoption and use of its strategic roadmaps.

1.2 Purpose and scope

This deliverable is part of the activities carried out in SPRINT WP3, which aims to increase the recognition of SNETP as a key player in the European energy landscape, in particular by identifying potential synergies between nuclear and other sectors but also by channelling interactions with peer organisations (technology platforms, SET-Plan, international agencies).

In line with this objective, it provides new ideas for the development of interactions with other industrial sectors. SNETP is currently engaged with a number of international nuclear R&D stakeholders such as for instance IAEA and EERA-JPNM. The platform aims to enlarge the scope of its interactions to other sectors in order to adapt its priorities and get ready to a changing context including but not limited to, increasing share of renewables in the energy mix, digitalisation, challenges around nuclear competitiveness and safety, decommissioning, etc (SNETP 2018b).

A total of nine synergies were consolidated in this study. They are expected to feed the update of the SNETP SRIA – a strategic document of the platform which hasn't been updated since 2013, and aims at shaping the long-term strategy of the platform (SNETP 2017). They were identified by adopting an open innovation workflow, looking at innovations from other sectors which could benefit to nuclear fission and on the contrary examining innovation from nuclear which could be of use for other technological sectors.

The following classification of synergies was adopted:

- Cost mutualisation
- Market output
- Technological improvement (cost reduction, lifetime extension, efficiency improvement…)
- Improved working conditions
- Strategic advantage

Then, these synergies are characterised using the following criteria:

- Impact that the synergy is expected to have on each industry
- Maturity of the innovation from which the synergy could emerge
- Number of barriers preventing from replicating the innovation in the other industry
- Number of drivers facilitating the replicability of the innovation in the other industry

The scope of the desktop research is international but aims to inspire innovation and research for European R&D stakeholders.

1.3 From closed to open innovation

1.3.1. Closed innovation workflow

Traditionally, innovation has been defined as a linear process to find a solution for existing or expected challenges:

1. The first action to be conducted is the identification of challenges which enables to properly identify the problem;
2. Second, a research program is launched in the most promising directions to address this problem;
3. Research brings solutions:
    a. One solution is chosen as the most appropriate one and is funded and developed.
    b. The other solutions are discarded.
    c. Sometimes, none of the different research directions brings any solution or they bring interesting results but are unable to solve the initially identified problem.
4. A marketable product is developed out of the most suitable solution and this product addresses the challenges identified in the first place.

This basic workflow is called **closed innovation** (depicted in Figure 1). As may be seen, closed research programs use few existing solutions from outside the program boundaries (outside world) to build their own solutions. Yet, no research program is 100% closed. Downstream in the workflow, the specificity of closed innovation programs is that only the most appropriate solution is developed, while the second-class solutions have no further applications: they remain unexploited.

1.3.2. Open innovation workflow

The open innovation workflow is quite different. At any stage of the research project, stakeholders from outside the project can bring their solutions/innovations into the project or use some outputs of the project for their own research.

Thus, once the challenge has been defined at preliminary stages, the outside world (partner companies, other industries, other research institutions, etc.) brings pieces of solutions which either solve part of the problem or provide technical solutions to solve the problem (e.g. last technology experimental means). Early-stage open innovation mechanisms may include: idea competitions, innovation networks, community sourcing, crowdsourcing.

Later in the process, there are still some opportunities to take inputs from the outside world (e.g. user immersion or *lean startup* techniques to ensure that the design and development steps fit future customers' expectations). Yet, most exchanges would happen in the other direction: the preliminary outputs of the project can be used in the outside world even though they are not sufficient to solve the initial problem.

If these outputs are not strategic for the research program and the rest of the organisation's activity, they can:

1. Feed other research projects through academic publications or research partnerships;
2. Be exploited by employees to create spinoff companies (intrapreneurship);
3. Be patented and sold or licensed to other innovating organisations to develop new products in new markets.

Besides, some open innovation mechanisms are flexible and facilitate exchanges at all stages:

- Collaborative research & development programs (e.g. long-term agreements between partner organisations);
- Product platforming (e.g. software development toolkits SDK and application programming interface API)

Finally, at the end of the process, the outputs which are the core of the innovation to solve the initial problem would usually not benefit the outside world directly. As shown in Figure 1, they would rather be used to develop new products for existing markets following the conventional innovation path. However, those new products may still be useful to future open innovation projects.

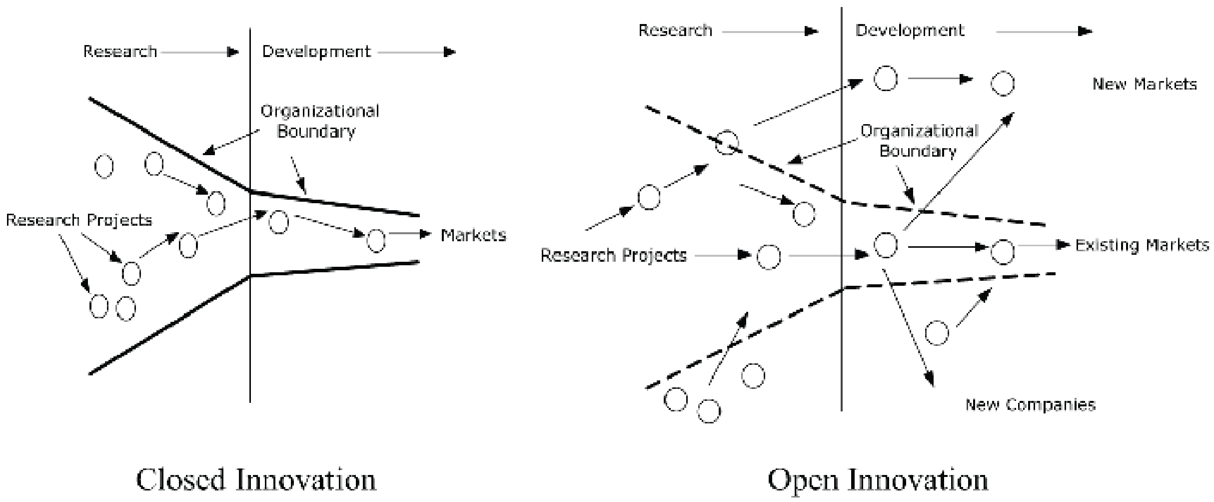

Figure 1 – Open vs closed innovation concepts (Chesbrough 2006)

1.4 Innovation in national, European and international ecosystems

Different sources were investigated to identify these synergies.

1.4.1. Innovation in European Technology Platforms

European Technology Platforms (ETP) are industry-led, multi-stakeholder clusters recognised by the European Commission in which European stakeholders from the same technological sector define and organise their strategy, mobilisation and dissemination actions. In particular, they agree on common priorities and then draft and implement strategic research and innovation agendas. Being part of an ETP is also a key enabler to foster networking opportunities with other platforms to address cross-sectoral challenges and to look for international cooperation.

ETPs are in close contact with the European Commission. The EC supports ETPs by providing them a dedicated contact point in relevant Directorate-General, by organising cross-ETP workshops and by consulting them on implementation aspects of H2020.

They are currently organised in seven groups:

- Bioeconomy (Aquaculture, Animal Health, Animal breeding & reproduction, Agri-food, Forest, Plants, Organic food & farming)
- **Energy (Biofuels, Photovoltaics, Ocean energy, Heating & Cooling, Smart grids, Nuclear energy, Wind energy, Carbon capture & storage)***
- Environment (Water supply & sanitation)
- **ICT (Embedded systems, internet of things & digital platforms, Nanoelectronics, Smart systems integration, High performance computing, Robotics, Digital media, Software & digital services, Telecoms, Photonics)***
- Production and processes (Construction, **Steel industry**, **Advanced materials**, Textile, Manufacturing, Nanotechnologies & medicine, **Mineral resources**, Chemical industry)*
- Transport (Aeronautics, Logistics, Rail, Road, Waterborne)
- Cross-cutting ETPs (Nanotechnologies, Industrial safety, Consumer goods)

Some ETPs are cross-cutting by nature. For instance, due to the wide adoption of digital technologies, most ETPs within the ICT group involve more than their own industrial sector (e.g. 3D nuclear simulation is one of the existing applications of high-performance computing). Because they provide generic products (steel, advanced materials, raw materials, chemical industry) and services that facilitate networking and interactions (smart grids), other sectors are also cross-cutting.

* Potential synergies between nuclear industry and the **ETPs in bold** were considered with a particular scrutiny in this study.

1.4.2. Other European innovation initiatives

- **European Institute of Innovation and Technology**

Created in 2008, the European Institute of Innovation and Technology (EIT) is a unique EU initiative that boosts innovation and entrepreneurship across Europe following the idea that strength comes from diversity.

It supports the development of dynamic pan-European partnerships between leading universities, research labs and companies. Together, they develop innovative products and services, start new companies, and train a new generation of entrepreneurs. They bring ideas to market, turn students into entrepreneurs and support business innovation. These partnerships are known as EIT Knowledge & Innovation Communities (KICs).

KICs are divided in different categories: Climate KIC, EIT Health, EIT Digital, EIT Raw Materials, InnoEnergy, etc. For the purpose of this study, only InnoEnergy, a partner of the SPRINT project, will be considered.

- **European Innovation Partnerships**

EIPs act across the research and innovation chain, bringing together all relevant actors at EU, national and regional levels in order to: (i) step up research and development efforts; (ii) coordinate investments in demonstration and pilots; (iii) anticipate and fast-track any necessary regulation and standards; and (iv) mobilise 'demand' in particular through better coordinated public procurement to ensure that any breakthroughs are quickly brought to market. Rather than taking the above steps independently, as is currently the case, the aim of the EIPs is to design and implement them in parallel to cut lead times.

EIPs streamline, simplify and better coordinate existing instruments and initiatives and complement them with new actions where necessary. Therefore, they build upon relevant existing tools and actions and, where this makes sense, they integrate them into a single coherent policy framework.

EIPs are launched only in areas, and consist only of activities, in which government intervention is clearly justified and where combining EU, national and regional efforts in R&D and demand-side measures will achieve the target quicker and more efficiently.

EIPs are divided in six categories: Agriculture, Smart Cities, Raw Materials, Water Efficient Europe, Active and Healthy Ageing and General information. For the purpose of this study, a specific focus was made on the EIP dedicated to Raw materials. The first two targets of the EIP (EIP Raw Materials 2013), as stated in the Strategic Implementation Plan, are addressed in this deliverable:

- Up to ten innovative pilot actions on exploration, mining, processing, and recycling for innovative production of raw materials;
- Substitutes for at least three applications of critical and scarce raw materials.

1.4.3. National and International Organisations

These below mentioned organisations were identified on a case by case basis according to the challenges faced by the nuclear sector, as recognised in the SNETP and NUGENIA roadmaps. In order to find solutions to address these challenges, the study of the SRIAs of the targeted ETPs was completed by a scrutiny of the innovations researched and sometimes developed by the following organisations.

- **International Atomic Energy Agency (IAEA)**

The International Atomic Energy Agency (IAEA) is *"the world's central intergovernmental forum for scientific and technical co-operation in the nuclear field. It works for the safe, secure and peaceful uses of nuclear science and technology, contributing to international peace and security and the United Nations' Sustainable Development Goals*."(IAEA, n.d.)

In order to achieve this goal, the IAEA organises on a regular basis events gathering various stakeholders and experts (regulators, safety authorities, utilities, government, etc.) but also courses, workshops and fora. The institution also drafts reports aimed at assessing the global status and analysing the trends in fields of nuclear science and technology. Those types of documents were the ones targeted in this study.

- **Nuclear Energy Agency (NEA)**

The Nuclear Energy Agency (NEA) is a specialised agency within the Organisation for Economic Co-operation and Development (OECD), an intergovernmental organisation of industrialised countries. It facilitates co-operation among countries with advanced nuclear technology infrastructures to seek excellence in nuclear safety, technology, science, environment and law. The NEA works as a forum for sharing information and experience and promoting international co-operation; a centre of excellence which helps member countries to pool and maintain their technical expertise and a vehicle for facilitating policy analyses and developing consensus based on its technical work (NEA, n.d.).

Certain policy analyses were investigated in the framework of this study.

1.4.4. National research institutes

Finally, some innovations were also identified in national research programmes and institutes such as the CEA, MIT, and Oak Ridge National Laboratory (ORNL).

These sources were relevant for the identification of early stage innovations.

2 Methodology

To assess potential interactions between SNETP and other European technology platforms or other industrial sectors, this study has adopted a 3-step methodology.

1. First, the aim of the first step was to identify and classify potential interactions with cross sectorial innovations. To do so, desk research was conducted to identify the main challenges that the nuclear sector face and complemented with interviews to experts. These potential innovations addressing the needs of nuclear are called **spin-in synergies**.
2. Second, the methodology analysed recent innovations from the nuclear sector that could be useful to address challenges in other sectors. These potential interactions are called **spin-out synergies**.
3. Finally, based on the maturity, the drivers and barriers of each innovation, the **opportunity of future interactions** was analysed: this deliverable will provide a synthesis and a list of recommendations to implement an action plan to go forward.

2.1 Identification and classification of potential upstream synergies

2.1.1. Nuclear energy challenges

The nuclear industry currently faces a certain number of challenges. To ensure a sustainable growth of this sector, these challenges have to be addressed in the coming years. In this study, the list of challenges identified for the nuclear sector are mostly taken from the SNTEP Strategic Research & Innovation Agenda (SRIA) document (SNETP 2013) and supplemented with all relevant documents found during the literature review. Then, the challenges are categorized (safety at work, economics, technological risks, lifetime extension, technological efficiency, etc.).

2.1.2. Definition and qualification of upstream innovations

Upstream innovations are innovations from the outside world expected to have a potential positive impact on one or several challenges of the nuclear sector if actions are taken to create interactions between the two worlds. Such interactions would create an "upstream synergy". As they may not be related to the nuclear sector yet, upstream innovations are to be found in the literature of the other sectors to be analysed (see the list of sectors in § **Erreur ! Source du renvoi introuvable.**). In particular, the strategic roadmaps and SRIA of the ETP corresponding to each sector are analysed.

Once upstream innovations have been identified and constitute a promising interaction opportunity, they will be classified and qualified, based on the following criteria:

- Sector of origin
- Challenge from the nuclear sector that could benefit from the innovation
- Potential or expected impact of the innovation
- Maturity of the innovation
- Barriers and drivers to spin the innovations into the nuclear sector

2.1.3. Validation and completion through expert interviews

Once potential upstream synergies have been identified and qualified, this assessment was validated and completed though interviews. Three interviews were planned with experts from the sectors in which main synergies have been identified.
The interviews will focus on the maturity of innovations, the barriers and drivers as well as possible promising innovations that would have been missed during the literature review.

2.2 Identification and classification of potential downstream synergies

2.2.1. Nuclear innovations potentially addressing downstream challenges

While upstream synergies can be identified by looking for outside-world innovations responding to nuclear challenges, downstream synergies are more difficult to foresee and identify. Indeed, these synergies arise from nuclear innovations which, at first, were not meant to have commercial applications outside the nuclear sector.

Potential synergies may still be identified if a nuclear innovation matches with a challenge of another industry. Yet, assessing all current challenges of the European industries is beyond the scope of this study. Therefore, this study voluntarily focused on a number of sectors (see § **Erreur ! Source du renvoi introuvable.**). These sectors are expected to embrace most potential synergies. Most matches will be found either:

- by looking for a nuclear solution responding to a challenge taken from the (SRIA) of other ETP;

- or by looking for potential applications for an existing nuclear solution identified in a recent annual report from nuclear research facilities or an expected nuclear solution found in a roadmap/SRIA. This approach is mostly achieved by conducting desktop research.

It should be kept in mind that many potential synergies were identified in this assessment. There are two reasons for that: first some significant synergies may still arise from sectors which were not included in the focus of this first assessment. Besides, some synergies are by nature unpredictable and non-exhaustive. Innovation can bring solutions to challenges not yet formulated (e.g. in artificial intelligence: an algorithm developed for nuclear simulation may very quickly be used in other applications).

2.2.2. Definition and qualification of downstream innovations

Downstream innovations are defined here as innovations from the nuclear sector which are expected to potentially have an impact on one or several other sectors. These innovations would indeed solve some challenges in these sectors if actions are taken to create interactions between the two worlds. Such interactions would create a "downstream synergy".

Once downstream innovations have been identified and constitute a promising interaction opportunity, they are classified and qualified, based on the following criteria:

- Sector(s) of destination
- Type of nuclear innovation and type of challenge
- Potential or expected impact of the innovation
- Maturity of the innovation
- Barriers and drivers to spin the innovations into the other sector

2.2.3. Validation and completion through expert interviews

Once potential downstream synergies were identified and qualified, this assessment was validated and completed though interviews. Three short interviews were conducted with experts from the fields in which the main synergies have been identified.

The interviews focused on the maturity of innovations, the barriers and drivers as well as possible promising innovations that would have been missed during the literature review.

2.3 Synthesis, recommendations and action plan

Finally, based on the barriers and drivers identified for each potential synergy, a synthesis and a list of actions was provided for each opportunity to move forward. The recommended actions will be proposed to SNETP governance at the occasion of a wrap-up meeting presenting all the SPRINT deliverables. The next steps would be to assess the feasibility, prioritisation and validation of the proposed actions and interactions.

3 Identification of potential spin-in synergies

3.1 Nuclear energy challenges

As explained above, open innovation opportunities often emerge from the identification of challenges. Some of the most important faced by nuclear energy today have been identified below.

3.3.1. Plant maintenance, safety and long-term operation

Plant safety and security, maintenance and long-term operation are interlinked challenges, currently confronted to a deeply contradictory context.

After the Fukushima accident in 2011, focus has been reinforced on the safety of the facilities. Several measures at the European level have been implemented to respond to this concern. They include carrying out 'stress tests' to reassess the design of nuclear power plants against site specific extreme natural hazards; installing additional backup sources of electrical power and supplies of water; and changes and reforms of organizational and regulatory systems (Jawerth 2016). Still, a large share of the public opinion in a country like France is convinced that a nuclear accident would have dramatic consequences (IRSN, n.d.). Even though the IRSN study shows that most people agree that no effort has been spared to ensure a high safety level, this low public confidence in nuclear safety undermines the perspectives for future nuclear new builds.

At the same time and in parallel of this rising concern, public authorities in several countries such as the United States (Baker 2017), have required the life extension of their NPPs leading to important investments to answer the related safety concerns. As a major part of the European fleet will be reaching its original lifetime in a decade (see Figure 2: Age distribution of operating nuclear reactors worldwide; Source: derived from IAEA, 2013) decisions regarding life extension will also have to be taken.

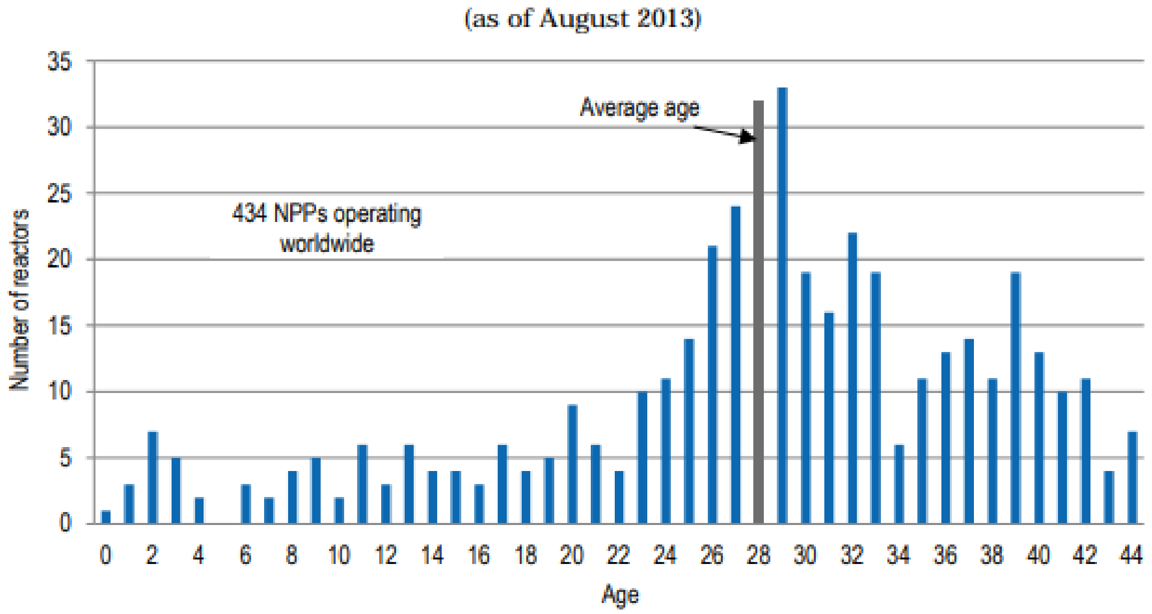

Figure 2: Age distribution of operating nuclear reactors worldwide; Source: derived from IAEA, 2013

Then, if decided, long-term operation and life extension of NPPs will arise concerns regarding the reliability of the components that are the most critical to safety and hardest to replace: the reactor pressure vessel, reactor internals and large concrete civil structures. Replacing any of these components would most likely be cost-prohibitive and lead to plant closure (Baker 2017).

Managing safely and efficiently the long-term operation of NPPs is a key condition to ensure the sustainability and prosperity of nuclear in the long term. To approve lifetime extension and new builds to cope with future energy needs, regulators usually require additional safety features and guarantees.

This challenge goes hand in hand with improving the reactor operation.

3.3.2. Improving nuclear power plant operation

The improvement of the reactor operation hides in fact a couple of sub-challenges, including operation economics and human organisational factors.

The first key sub-challenge is to improve the **operation economics**. Today, owners of NPPs operate in increasingly deregulated markets. This situation puts nuclear energy under pressure to be competitive with other energy production systems, an incomparable situation with regards to previously regulated markets. As explained in the previous section, this issue is compounded by more and more demanding safety requirements, increased maintenance efforts in the perspective of life extension and costs related to the management of spent fuel and dismantling driving the cost of nuclear electricity upward. For instance, in France, the *Cour des Comptes,* a financial body controlling the regularity of the accounts of public and private organisations for which the State is a shareholder, analysed in a 2014 report the evolution of the cost of electricity produced by nuclear in France and concluded that it was on the rise[1] (Cour des comptes 2014). This, added to the fact that the cost of electricity production from renewables is decreasing (REN21 2017) and the price of CO2 emissions set by the EU Emission Trading System is still not high enough to divert the European economy from fossil fuels, puts NPPs operators under pressure.

The second sub-challenge is the **understanding of Human and Organisational Factors (HOF)** to improve safety and optimise performance and efficiency characteristics of NPPs operation. Among others, important challenges are to:

a. strengthen the objectivity of safety judgments by using methods of risk-oriented decision making

b. understand the conditions required for ensuring the robustness of the organisations in charge of operating NPPs, based on a deep understanding of work practices and safety culture (Nugenia 2013).

3.3.3. Spent fuel management & decommissioning

The decommissioning of a nuclear installation such as a power plant or a research reactor is the final step in its lifecycle. It involves all activities from the shutdown and removal of nuclear materials to the environmental restoration of the site. The whole process can last a couple of decades.

By 2025, it is estimated that over a third of the EU's currently operational reactors will be at the end of their lifecycle and in need of shutdown, unless they will be extended. Within two decades, out of the 128 reactors (WNA 2018) currently functioning in the EU, more than half will be in a process of decommissioning. This situation may be compounded by the growing pressure in some countries to speed up NPPs closure and decommissioning, shorten overall schedules and cut the costs.

In conjunction to this situation, the amount of nuclear waste generated produced by the nuclear fuel cycle is increasing. For instance, if France operates its reactors until the end of their lifetime, the total amount of spent fuel (UOX, MOX) to be recycled will amount 30 000 tHM, which is around three times the current value which amounts to 12 000 tHM (Andra 2013).

[1] The Court takes into account three main costs of nuclear electricity production to estimate the levelized cost of electricity: past expenses (conception, cost of building the NPP, research), current expenses (fuel, personnel, taxes, security and associated research), future expenses (dismantling, management of spent fuel and associated research). From 2010 to 2013, in France, this cost goes from 49,6 € /MWh to 59,8€/MWh between 2010 and 2013.

3.3.4. Managing the changing rules of the energy mix

The share of renewables in the European energy mix is increasing quickly. The share of renewable energy as a fraction of total energy consumption in the EU-28 was 16.7% in 2015 and is on track to reach a 20% share of renewables by 2020. Wind power, transport biofuels, solar thermal in industry and buildings, biomass in industry and buildings and solar PV are expected to be the main contributors to this additional capacity (IRENA 2018).

Regarding power production, as a result of their non-dispatchability and priority of integration in the grid, the increase of renewables may result in a decrease of electricity production produced through nuclear. This evolution could have a significant negative impact for nuclear, whose power plants are known to be highly capitalised and to have a high fixed costs/variable costs ratio contrary to peaking plants. Indeed, the profitability of nuclear baseload power plants is related to their operating time.

In the French case for instance, for a 30% penetration of wind energy, the nuclear production loss is estimated to amount to 20% (Keppler and Cometto 2012). More precisely in this case, profitability of NPPs is decreased by two cumulated factors: the production decrease and the decrease of electricity prices in the wholesale electricity markets as the result of the introduction of renewables with low variable costs and temporary overcapacity. Any decrease of the nuclear production is significantly reflected in the revenues of the fleet. In France, for a 10% penetration of wind power and a corresponding decrease of 4% of nuclear production, the loss of revenues is estimated to amount 24% (Cany 2017).

To avoid this negative impact, key challenges for nuclear are to enhance its competitiveness and find new market outlets for its energy production and

3.2 Synergies coming from other sectors

To address these challenges, a wide range of innovations were identified as potential game-changers for the safe, competitive and reliable development and operation of NPPs of today and tomorrow.

3.2.1 Virtual Reality and digital twins

Definition. Virtual reality refers to a specific type of reality emulation which entails presenting our senses with a computer-generated virtual environment that we can explore in some fashion.

Application to Nuclear. Among the various applications of virtual reality, “digital twins” constitute one the most promising for nuclear. This sensor-enabled technology aims to produce a near-real time digital image of a physical system through massive, cumulative, real-time, real-world data measurements taken by sensors (Deloitte 2017). It is designed to model and monitor complicated assets or processes that interact in many ways with their environments for which it is difficult to predict outcomes over an entire product life cycle (ETP4HPC 2017). Three primary components are necessary to create a digital twin:

- first, the creation of a 3D virtual model;
- second, the creation of simulators that will feed into the virtual model;
- and finally the implementation of product lifecycle management (PLM) to centralize and organize data (Rosmorduc 2017).

Applied to nuclear energy, digital twins would enable to virtually access the reactor while it is functioning. This virtual access could help overcome a major constraint for maintenance and could bring key benefits in the overall efficiency of operation.

Figure 3 represents the concept of digital twins.

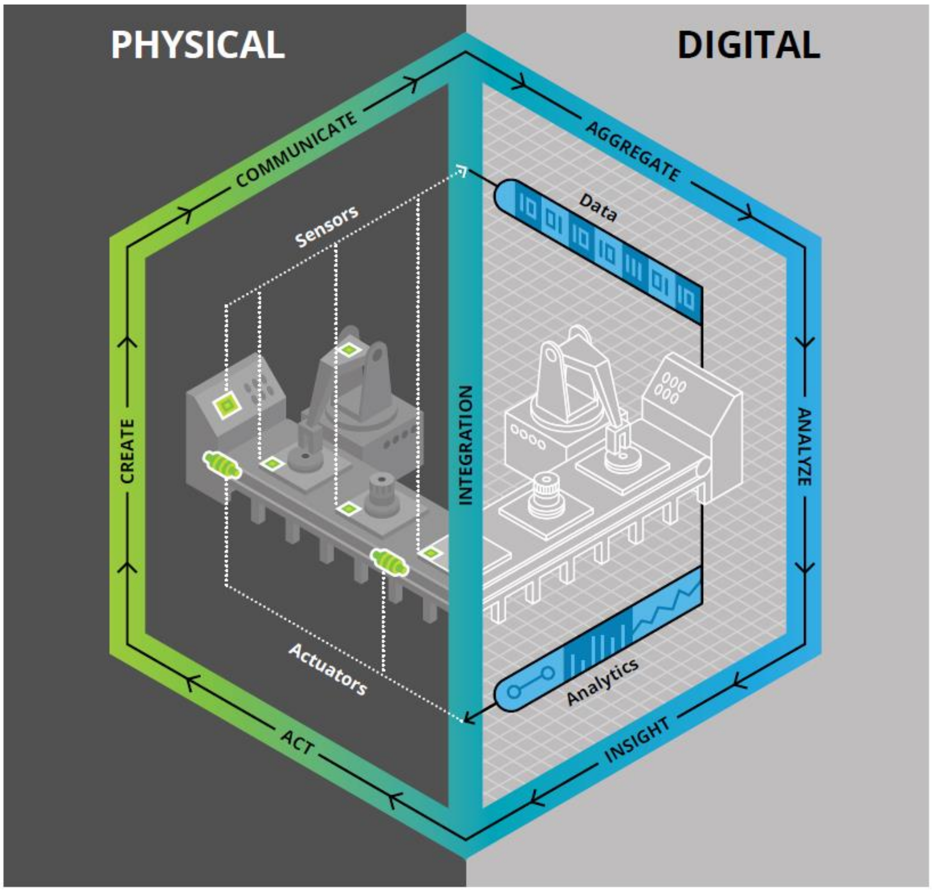

Figure 3 - Digital twin model process; Source: Deloitte University Press

Impact. It's worth reminding that a precise and regularly updated knowledge of the physical asset is at the heart of the preparation of all maintenance tasks. With digital twins, this task could be made a lot easier for NPPs. It would offer an opportunity for operators to solve physical issues faster by detecting and understanding them sooner, predict outcomes to a higher degree of accuracy, design and build more performant NPPs, and, ultimately, better serve the customers. In the end, an important number of impacts are to be taken into consideration:

- Reduction of maintenance downtime
- Increase of competitiveness
- Enhancement of nuclear safety
- Life extension of NPPs (Nugenia 2013).

Maturity. The emergence of increasingly favourable storage and computing costs (The Economist 2015) will enable a growing number of use cases and possibilities to develop NPP digital twins. General Electrics is currently piloting a digital windfarm concept that uses a real-time simulation and modelling system, enabling the windfarms to cope with a harsh environment and predict more easily the output of the farm. According to the company officials, the technology could boost a farm's energy production by up to 20% (Lempriere 2017a). In any case, virtual reality solutions are getting closer to market every day. The recent development by EDF of a digital innovation called "VVProPrépa", enabling to virtually visit the reactors, a solution already used for the "Grand Carénage" operation in Cattenom, witnesses this evolution.

Barriers. One of the primary challenges to creating a digital twin is complexity. A nuclear site can be spread over several kilometres and involves an important number of third parties. Yet, for an effective digital twin to function, a virtual model must be extremely precise and include even the tiniest of components. To come close to a digital twin, nuclear power plant operators must be able to gather data from suppliers, clients, simulators and on-site information.

Even if one manages to bring together all the necessary stakeholders, three important challenges are still to be addressed. Operators need to ensure the long-term reliability and viability of a digital twin throughout the expected NPP life cycle which is ranged between 60 to 70 years. Interoperability is another major issue. A digital twin unites multiple simulation tools often created by various contractors. A successful digital twin would imply that all of these tools could be standardized to ensure interoperability (Rosmorduc 2017). At last, if implementing digital twins seems profitable for the economics of Nuclear Power Plants at first sight, it may prove very costly to install sensors everywhere in the plant. A sustainable business model needs to be found and modelled prior to developing the technology.

Conclusions. Ensuring both the safety of nuclear facilities in the long term and the competitiveness of NPPs is key to keep nuclear among the sustainable ways of providing electricity. Implementing the concept of Digital twins could prove to be efficient in tackling these two challenges. If today, this solution hasn't been fully implemented yet in NPPs, the potential positive impacts it could generate motivate at least further initiatives on behalf of SNETP to consider the deployment of the technology. These steps going forward could be ranged according to their level of ambition and achievability:

1) Liaise with the digital ETPs to meet the digital community, identify key stakeholders and eventually acknowledge their research results in implementing digital twins in power plants.
2) Discuss the respective Strategic Research agendas and identify common issues of interest.
3) Coordinate joint research through either in-kind projects financed within the SNETP Community or EU-project to research on the previously identified common issues of interest
4) Formalise this link in the long term by signing a Memorandum of Understanding between the platforms

3.2.2 Robotics and drones

Definition & context. NPP operation combines a number of interlinked human, organisational and technical factors. Robots and drones are likely to play an important role. The first patents in the field of robotics appeared in 1954 and the robotic industry started to emerge in 1960s. From 1980 on, the rate of new robotics started to climb exponentially. For a while the main focus of science fiction and literature, robots became recently a viable part of the workforce and the issue is now taken seriously by the scientific community. The MIT in a 2017 study showed that in the USA, the introduction of one robot for 1 000 employees led to the disappearing of 5 to 6 jobs (Acemoglu and Restrepo 2017). It will soon become an inescapable sector of the economy and Nuclear Energy should be no exception (euRobotics, iTechnic, and RURobots 2014).

Impact. Major catastrophes in the nuclear industry (Three Mile Island, Chernobyl and Fukushima accidents respectively in 1979, 1986 and 2011) occurred even in the presence of high-tech control systems and mechanisation. These events fostered the research in robotics technology. This goes together with the increasing concern over the human safety and environmental protection.

The IAEA strongly favours the use of robots in NPPs (Varjonen, n.d.). Indeed, using robots could be particularly beneficial for several reasons:

1. Teleoperated robots would handle high risk movements in hazardous environments and tasks ranging from scrutiny and general maintenance to decontamination, post accidental activities and decommissioning. The environments of NPPs offer high temperature and radiation areas thus making human approach limited. Using robots would therefore avoid the need of human

inspection to measure radiation level and temperature. Such high-risk movements could include:

- o Inspection of reactor assemblies, pressure vessels, pipelines and assists in examination.
- o Cleaning up floors, generators and storage tanks

This previous statement is supported by the fact that 88 reactors are currently considered in a shutdown and decommissioning state around the world (‘Nuclear Decommissioning : Management of Costs and Risks’ 2013). The use of robots could ultimately eliminate or drastically reduce the need for maintenance downtime, by providing on-line maintenance facility, which as a result would enhance the NPPs’ competitiveness.

2. NPPs also benefit from other universal advantages of robots including working with precision without any interruption during outage (Iqbal 2012), but also including the ability to spot anomalies in sites that the human eye could miss.
3. Finally, decommissioning nuclear sites requires a lot of monotonous dismantling, tasks well suited to robots whose productivity is not deterred by fatigue or boredom (Lempriere 2017b).

State of the Art & Maturity. A strong drive to opt for advanced robotics in nuclear industry appeared after the Three Mile Island incident (Iqbal 2012). Among the first robots to be developed, a so-called System in Service Inspection (SISI) robot, remotely controlled, was used for the inspection of the troubled zone. The robot televised photographs from the contaminated zone, collected samples and radiation readings for further testing. Then, *Fred* robots – a six wheeled mobile unit controlled remotely – were used to swab the surfaces in contaminated areas. In addition, a series of three Remote Reconnaissance Vehicles (RRV) was deployed for inspection, surveying and cleaning operations. Several general purpose robots were then used by different operators such as KAERI and CANDU. These robots were highly task-specific with little intelligence, due to technological limitations and unavailability of integrated sensors. They were therefore unable to cope with any other scenario to which they were not designed to react.

Several machines are currently in use by utilities and operators, such as:

1. *Maestro* robot, equipped with a manipulator arm and a live supervision software, is being used by the CEA to conduct measures, saw off, and proceed to decontamination activities in highly radiated areas (CEA 2016).
2. *MIS* should also be mentioned. It’s a machine of 12 tons and 7 meters high equipped with camera, computed radiography, ultrasound, remotely controlled thanks to fibre cables which is used to scrutinize the tank.
3. *RIANA,* imagined and developed by AREVA can achieve a wide range of different missions: 2D and 3D cartographies, collection of samples, radioactivity measures. Among its key characteristics, RIANA is a modular robot, not designed for a specific activity, which brings flexibility to the operator (Le Ngoc 2015).

The development of integrated circuits in the 1990s significantly facilitated developing this kind of more autonomous robots for NPPs, moveable and equipped with integrated manipulators.

It can be said that the use of robots has continuously increased but there is room for breakthrough and innovation. The next generation of robots will be multi-task oriented robots, able to perform many activities with intelligence and with the capability to tackle unwanted situations. In NPPs, these new robotic systems are expected to work efficiently in full autonomous mode in contrast to the current man-operated or semi-autonomous scenarios. However, to be able to achieve this type of actions, robots need to incorporate artificial intelligence, improved sensors capability, enhanced data fusion and compliant human like leg and hand structures for efficient motions.

Research in the field is already ongoing. A UK-based laboratory[2] is currently conducting a four-year research project on the potential uses of robotics within the nuclear sector. Their robots include high-performing visual imagining systems, along with robotic arms. The laboratory is building on the knowledge and experience acquired in space robotics. Nuclear and space environment have in common the fact that they are remote and hostile. Space industry had to develop autonomous software to deal with locations far from Earth, preventing remote operation. Therefore, in most demanding space missions, software has to be reliable and robust. The same goes for NPPs. Moreover, hardware of the robotic systems designed for space and nuclear industries need to be radiation proof (Lempriere 2017b).

Barriers. There are still barriers to replicability.

- For now, there is still a limited number of actions one robot/drone can achieve, specific designs/materials can be necessary in a nuclear environment.
- Another challenge for the deployment of robots in NPP is the nature of the nuclear industry, a sector in which a change can take a long to be accepted (Robinson 2017) and which has historically taken a risk-averse approach in its operations and activities and continues to give priority to the avoidance or minimization of risk ('Managing Organizational Change in Nuclear Organizations', n.d.).

Conclusion. Improving nuclear power plant operation and managing safely their decommissioning are key to the public acceptance of nuclear. If robots take over the human personnel in conducting risky operations, the latter will have a reduced exposition to radioactivity. Significant investments in artificial intelligence sustain this eventuality (McKinsey 2018). Moreover, the ability to maintain the nuclear power infrastructure may depend on robots being able to carry out maintenance tasks that would otherwise be impossible, thus significantly extending the lifetime of reactors (euRobotics, iTechnic, and RURobots 2014). Although there are a couple of barriers, given the huge impact the use of robots would represent for nuclear, we believe it is urgent for SNETP to carry out a couple of actions.

These steps going forward could be ranged according to their level of ambition and achievability:

1) Liaise with the euRobotics initiative, which has set up Topic Groups[3] to address applications of robotics (including space, industry, logistics, etc.), in order to support the inclusion of nuclear applications in its future SRA (post-2020)
2) Develop joint research projects with the robotics community, on identified issues of common interest
3) Formalise this link in the medium term by signing a Memorandum of Understanding between the platforms

[2] The Surrey Technology for Autonomous Systems and Robotics (STAR) lab
[3] https://www.eu-robotics.net/sparc/topic-groups/index.html

3.2.3 Energy storage

Context and reminder of the challenge. With the increase of renewables in the electricity mix, nuclear takes the risk of not being used at maximum load, leading to a situation where its competitiveness is de facto decreased as reminded in section 3.3.4. This could be remedied with the storage and the identification of innovative and valuable market outlets for the nuclear electricity. Two options are specified below including hydrogen as well as large scale storage techniques using hydropower. Other storage options such as chemical and second life EV batteries could also be interesting solutions but are not addressed in this report.

Hydrogen: process, benefits and limits. During periods of high renewable production, instead of decreasing the load of Nuclear Power Plants, their output could be used to produce other valuable and energy carriers such as hydrogen. Hydrogen would be produced by decomposing the water molecule in hydrogen and oxygen through electrolyses.
Some recently published studies highlight the market potential of hydrogen, which could represent 2,500 € billion in 2050. Hydrogen could also play a major role in the energy transition: enabling large-scale renewable energy integration and power generation, acting as a buffer to increase energy system resilience, decarbonizing transportation, and helping to decarbonize building heat and power (McKinsey 2017).

As far as nuclear is concerned, benefits could flow in both directions. The production of hydrogen would enable to avoid the reduction of the load for NPPs. On the other hand, using economic nuclear electricity to produce hydrogen would turn out to decrease the production cost of hydrogen, which is very dependent on the cost of electricity. Nonetheless, detailed business models remain to be developed in this field. Specific nuclear power plants may be developed proposing both hydrogen and power supply (Cany 2017). A specific section is dedicated to the potential benefits of nuclear cogeneration (see § 4.3)

Storage through hydropower: process, benefits and limits. The pump hydroelectric energy storage (PHES) could also be a way to store the electricity produced by nuclear. Such system is composed of two pools located at different altitudes. When the demand for electricity is low, the system pumps water from the lowest reservoir to the highest. When the demand and electricity prices are high, the stored water is released through turbines to produce electric power. PHES is the only proven large scale energy storage scheme for power system operation, with increasing trend of installations and commercial operation in recent years (Shafiqur Rehman, Luai Al-Hadhrami, and Mahdub Alam 2015). If PHES is considered mostly today as a relevant solution to make the most of the electricity produced by renewables, it could also be applied to nuclear in order to avoid the load reduction and its subsequent loss of competitiveness.

PHES plants have several intrinsic advantages such as flexibility to start/stop, fast response speed, capacity to track load changes, adaptability to drastic load changes, modulating the frequency and maintained voltage stability. The energy efficiency of PHES varies in practice between 70% and 80% with some claiming up to 87% (Shafiqur Rehman, Luai Al-Hadhrami, and Mahdub Alam 2015). However, the low availability of sites is an important barrier for the large deployment of this solution.

Conclusions. In a context where the share of renewables in the European electricity mix is increasing quickly, it is worth noting the environmental and economic potential of these two techniques. They make it possible to integrate high shares of low-carbon energy into a given mix by avoiding both reducing the baseload power of nuclear and the restriction of non-dispatchable renewable energy. If proven business models are still to be identified, especially for hydrogen, the positive impacts of these techniques at least justify carrying out further studies on hybrid power plants combining nuclear with hydrogen production and investigating new sites for PHES.

4 Identification of potential spin-out synergies

4.1 Recovering critical raw materials from spent fuel

Challenge faced in the raw material sector. Raw materials are crucial for the sustainable functioning of the EU economy and any industrial production in general. In Europe, some of them are called critical when they combine a high economic importance and a high risk of supply. Critical raw materials (CRM) are present in many essential products like electric motors, autocatalysts, batteries and micro-processors. The supply risk for the EU is mainly related to the resource scarcity and the fact the worldwide production is located in a small number of countries on which the EU industry relies heavily. To mitigate those risks, several European research initiatives have been initiated corresponding to over €250 million from 2018 to 2020 (Chavardes and Bazin-Retours 2018).

Potential solutions include the use of **substitute materials** and **recycling the CRM** from end-of-life products. Rare Earth Elements[4] (REE) and Platinium Group Metals[5] (PGM) are part of the CRM and among the most difficult to substitute. Recycling solutions should therefore be further investigated and developed.

Description and expected impacts of the innovations. During nuclear fission reactions occurring in power reactors, atoms which are lighter than uranium are formed. They are called fission products. Research on the reprocessing of spent fuel has made it possible to accumulate considerable expertise – especially in chemical processes – for the selective recovery of metals and materials of interest in nuclear spent fuel. Based on their relative abundance in spent fuel compared to their annual world production and based on their stability/radioactivity in spent fuel, REE and PGM were identified as the most promising elements to recover (Bourg and Poinssot 2017).

Currently, even in countries where spent fuel is reprocessed like France, REE and PGM are not recovered. In the case of France, calculations show that recovering some of these CRM could represent a significant annual production (Bourg and Poinssot 2017):

- REE
    - Samarium: 0,2% of world production
- PGM
    - Ruthenium: 21.8% of world production
    - Rhodium: 3.5% of world production
    - Palladium: 1.2% of world production

The potential impact is higher if all the spent fuel discharged annually in the world is considered: 100% of global Ruthenium requirements and 10% of Palladium needs.

As a **direct application** of the expertise gained in the nuclear sector in chemical processes, the recovery of CRM from nuclear spent fuel could certainly have a positive impact on the supply of some raw materials. Besides, there might also be **indirect synergies** with broader impact on the supply of raw materials. Indeed, even though it may not be economical to recover all REE and PGM from the spent fuel, extensive knowledge on the chemistry of REE and PGM could be transferred in other sectors to develop recycling processes (e.g.: recovering of REE from the magnets of electric motors, from smartphones, improvement of the recovery of PGM from autocatalysts,…).
Maturity, barriers and drivers to recover critical raw materials.

[4] China is responsible for around 95% of total production (Deloitte et al. 2017)
[5] The main 2 PGM are produced by South-Africa (64% of Platinium) and Russia (44% of Palladium) (Deloitte et al. 2017)

The process to recover ruthenium during fuel reprocessing has already been tested as ruthenium was known to cause issues in the vitrification process (Bourg and Poinssot 2017; Babain et al. 2002; Enokida et al. 2009). The maturity for the recovery of REE and PGM is lower. Despite the apparent absence of technological barrier to the recovery of ruthenium, there are a few barriers to the adoption of such innovation:

- ***Radioactivity***
  In the spent fuel, REE and PGM include radioactive isotopes with significant activity levels. Interim storage would therefore be necessary before re-using recovered elements. While the activity of ruthenium decay rather quickly (a 30-year interim storage is enough to fall below IAEA thresholds), radioactivity is a barrier to the recovery of most other elements (Bourg and Poinssot 2017).
- ***Declassification***
  Even when radioactivity falls below non-harmful thresholds, some countries like France have no regulatory framework allowing the declassification of nuclear materials to be reused in other industries.
- ***National fuel-cycle strategies***
  The potential recovery of CRM from spent fuel is limited to the number of countries where a reprocessing strategy has been adopted.

Regarding indirect synergies, the only barriers to an efficient knowledge transfer of CRM chemistry expertise from the nuclear sector to other industries are:

- ***Existence of a dedicated framework***
  In France, CEA initiated a network of European stakeholders to promote innovation in mineral processing for mining and recycling called Prometia[6]. CEA also launched the European Institute of Hydrometallurgy with the aim of providing a test-bed site for innovations transferred from nuclear chemistry to hydrometallurgy. As a result of this dynamic, a start-up called Extracthive is born, but further similar initiatives would be necessary to reinforce this framework which is essential to ensure a successful transfer from the nuclear sector to hydrometallurgy.
- ***Incentives from the markets involved***
  Pushing innovation transfer is useless if there are no market opportunities pulling for those innovations. While there are already trade opportunities for autocatalyst recycling, the recovery of REE and the smartphone market seem to take opposite directions. Indeed, the smaller the electronic components are, the harder the recovery of valuable elements are. That is why recovery processes may have to focus on applications with better market perspectives like REE magnets that could be found in electric motors and wind turbines (Yang et al. 2017).

Conclusion and suggestions. Substitute materials and recycling solutions are necessary to address the challenge of reducing the European dependency on critical raw material imports. Nuclear spent fuel is one of the potential secondary source of CRM that has been investigated. It contains a number of CRMs in variable quantities, including rare-earth elements (REE) and platinum group metals (PGM). While ruthenium seems to be the most promising CRM to recover (based on economic significance), some barriers (radioactivity, national fuel strategies) make it unlikely to happen in the coming years. In the shorter term, the main synergy between spent fuel management and CRM supply is probably a transfer of knowledge from the nuclear industry to the growing industry of recycling: the experience gained in the chemical process required to filter specific elements during fuel reprocessing could be used to filter valuable materials in end-of-life products. Creating and strengthening the framework for such transfer could be an efficient action involving SNETP, as well as analysing the market

[6] http://prometia.eu/

perspectives. Building on the Memorandum of Understanding signed in 2016 by SNETP and the Joint Programme on Nuclear Materials of the European Energy Research Alliance (EERA-JPNM), working group of experts could be created on critical raw materials in the nuclear sector. A dialogue with the recycling industry could also be engaged (for instance the leading environmental industry company Veolia has opened a business line on nuclear cleanup[7]).

4.2 Recovering xenon for the aerospace sector

Challenge faced in the aerospace sector. The main challenge in space missions is to reduce any excess weight to maximise the payload. Recently, this challenge has accelerated the emergence and the adoption of fully electric satellites. Unlike conventional rocket engines, the propellant used in the thrusters of these satellites don't carry the energy required to propel the exhaust. The propellant of conventional rocket engines includes combustible materials – the energy from the combustion is what propels the exhaust – while electrical satellites only carry a neutral gas (xenon) and solar panels. Once in orbit, the electricity from solar panels is used to ionise xenon in the thruster which expels the gas. While conventional rockets are still adapted to put the satellites in orbit (a huge amount of energy is necessary for a short period), electric thrusters are much more efficient for the low-energy and long-term requirements of satellites.

Yet, natural xenon resources in the atmosphere are scarce and the continuous growth of demand for electrical satellites will require an increase in supply, as illustrated by recent industrial developments by Air Liquide (Air Liquide 2016). Currently, xenon is produced as by-product of oxygen and nitrogen separation (annual production of 53 000 kg (Herman and Unfried 2015)), which complexifies the ramp-up as oxygen and nitrogen markets drive xenon production.

Description and expected impact of the innovation. Xenon is one of the decay products of uranium. Currently, xenon remains in the nuclear spent fuel, unrecycled for re-use. Rough calculations show that every tonne of uranium burnt during 3 years in a conventional nuclear reactor would produce around 5,4 kg of xenon (Palcsu et al. 2002; Aregbe et al. 1996). This means that the renewal of spent fuel by 10 000 tonnes of fresh uranium could annually represent the equivalent of 1 year of conventional xenon production, while the current annual uranium consumption is around 60 000 tU (OECD Nuclear Energy Agency and International Atomic Energy Agency 2016). Some countries like France reprocess the spent fuel, but xenon has not been recovered until now. The development of specific processes to recover this gas could change this situation. Indeed, several technological solutions have emerged and could make xenon recovering feasible in the coming years (Jubin 2008; PNNL 2016).

Maturity, **barriers and drivers to recover xenon**. Little information is available on the maturity of the recovery processes mentioned in this section. Yet, the cryogenic process recovering both xenon and krypton is said to have reached commercial maturity (Jubin 2008). Therefore, the main barriers to a broad recovery of xenon from spent fuel is not technical but rather related to the national strategies to reprocess nuclear spent fuel or not. On the other hand, one economic incentive could be the growing demand of xenon for satellite thrusters. This is not yet the main end-use of xenon, but it could drive up the price of xenon in the next decades. Further market analysis would be necessary to compare the incentive to recover xenon with the investments necessary to reprocess spent fuel.

Conclusion and suggestions. The accelerated emergence and adoption of fully electric satellite has raised issues about the availability of xenon resources required to fuel ion thrusters. While the annual

[7] https://www.nuclearsolutions.veolia.com/en

production of xenon is currently around 50 t, nuclear reactors could boost this production significantly. Indeed, as a decay product of uranium, 50 additional tonnes of xenon could be produced by reprocessing 1/6th of the nuclear fuel used every year. The main barrier to this potential synergy between nuclear and aerospace is therefore the national strategies to reprocess spent fuel or not. SNETP could lead an action to better analyse the economics of recovering xenon in the nuclear industry.

4.3 Cogeneration to supply industry, cut CO_2 emissions and store energy

Challenge faced in the industry. Competitiveness and decarbonisation are two important challenges for the European industry (European Commission 2017). Both are closely tied to energy issues. On the one hand, energy is a major input of industrial activities which is why supply disruptions or price peaks can jeopardise any business in this sector. Many industrial activities require both power and heat, while the conditions for a steady supply of both inputs under long-term fixed-price contracts are challenging to fulfil.

Besides, the European industry is a significant CO_2 emitting sector. Most CO_2 emissions still come from power production according to IEA. However, in the “2-degree scenario” (2DS), industry is expected to become the first emitting sector in the coming decades (International Energy Agency 2016) (cf. Figure 4). Indeed, a successful development of renewables could decarbonise power production and the deployment of EVs could limit the emissions in the transport sector, but cutting CO2 emissions in the industry seems more challenging.

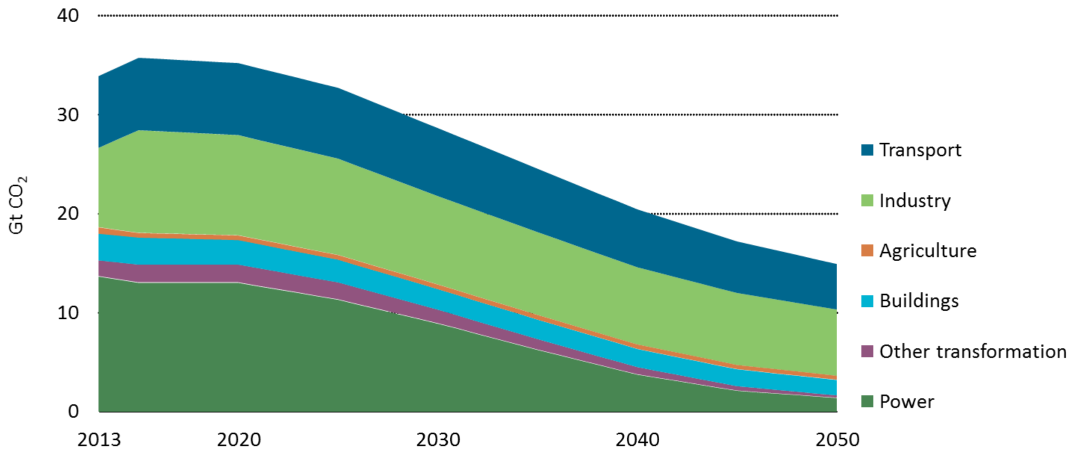

Figure 4 – Energy and process related CO_2 emissions by sector in the 2DS (International Energy Agency 2016)

Finally, beyond the industry sector, there is a growing need for power storage. This is mainly due to the development of intermittent energy sources and the increasing need for energy storage solutions used as a substitute for conventional fuels in the mobility sector. Apart from power batteries, some solutions based on the conversion of hydrogen could emerge in the future requiring sustainable ways to produce hydrogen.

Description and expected impact of the innovation. The principle of cogeneration is depicted in Figure 5. Cogeneration, either based on nuclear, renewables or conventional fuels, has a positive impact on energy efficiency and therefore on CO_2 emissions compared with conventional systems.

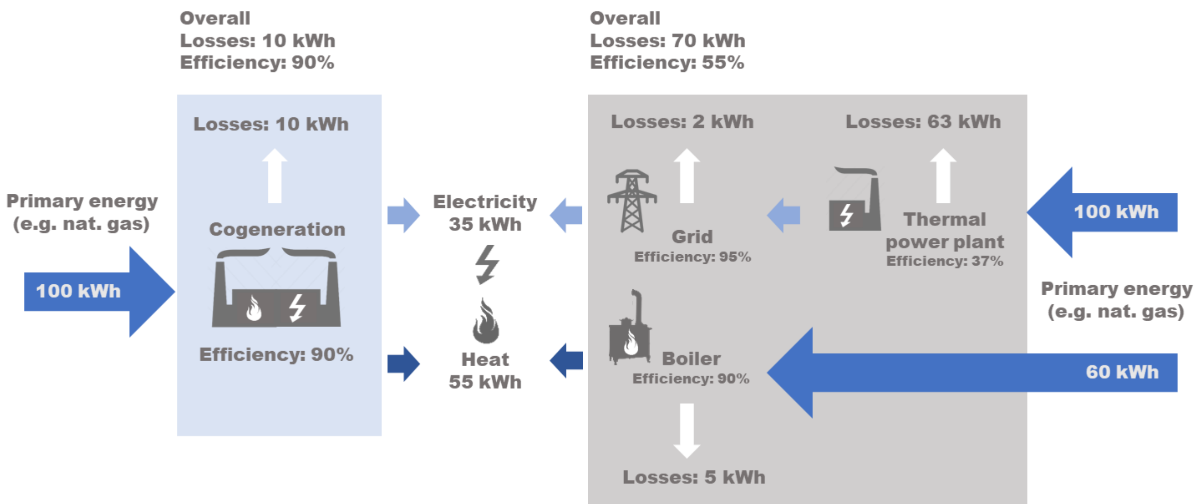

Figure 5 – Comparison of cogeneration and conventional systems for heat and power generation

Compared to conventional cogeneration, nuclear and renewable cogeneration systems are not only very efficient but also almost completely carbon-free solutions. Neither do they emit airborne pollutants like conventional cogeneration.

Even though IEA has not so far modelled nuclear cogeneration individually, the agency identifies this technology as one solution to contribute to the reduction of CO_2 emissions and help meet the objectives of its "below 2°C" scenario (B2DS) (International Energy Agency 2017). Avoided CO_2 emissions are hard to quantify as they depend on the previous systems that nuclear cogeneration would replace. Nevertheless, the feedback from past experience shows that it can have a significant impact: for instance, the nuclear-based district heating system implemented in Beznau, Switzerland (15,000 end users) has operated for 25 years and saved 46 $MtCO_2$ every year (International Energy Agency 2017).

Besides, nuclear cogeneration could offer a unique solution for high temperature applications (>250°C). Indeed, high temperature reactors (HTR) and very high temperature reactors (VHTR) could produce heat up to respectively 750°C and 1000°C in the future, surpassing conventional cogeneration systems and cogeneration based on renewables. Most applications requiring such high-temperature heat are industrial processes. Compared to the volatility of fossil fuels and the intermittency of renewables, nuclear can offer a steady supply of heat (constant flow at fixed price under long-term contracts).

Industrial application areas of high-temperature nuclear cogeneration include for instance the chemical and petrochemical sectors, and in the longer term, steelmaking (in particular the development of "ultra-low CO2 steelmaking" programmes). Ensuring a low carbon energy supply in these industry has become a priority in the relevant European Technology platform: this is objective n°1 for the European Steel Technology Platform (ESTEP 2017) and objective n°3 for the European Technology Platform for Sustainable Chemistry (SusChem 2017).

Finally, one potential application of nuclear cogeneration is the production of hydrogen (sometimes called tri-generation since hydrogen is an energy carrier like heat and power) based on the high-temperature electrolysis technology (which has a higher efficiency than power-based low-temperature electrolysis). This is one of potential solutions to produce low-carbon hydrogen for energy storage (power storage or hydrogen mobility). Longer term H2 production solutions such as thermochemical cycles are also investigated.

Maturity, barriers and drivers to develop nuclear cogeneration. Depending on the industrial application requirements, nuclear may already offers turnkey solutions. Indeed, current light-water reactors can already be used for low-temperature applications like district heating, desalination and processes in the paper industry (Auriault, Fütterer, and Baudrand 2015), on top of power production. For industrial applications requiring higher temperature (> 250°C), specific nuclear technologies are necessary. Modular HTR reactors are being developed to this end. The technology is mature enough to conduct the design, licensing and construction phrase. One HTR reactor is expected to get connected to the grid this year in China. Yet, for cogeneration applications, additional demonstration plants are necessary before heat is supplied to industrial users. An ongoing H2020 project (Gemini+[8]) aims at defining the design of such demonstration plant. This project also aims at defining the business plan of such plant. A good visibility on European industries that could be interested in combined heat & power supplied by nuclear plants will be necessary.

Conclusion and suggestions. European industry faces a double challenge to which nuclear cogeneration can bring solutions, namely competitiveness and decarbonisation. Indeed, cogeneration improves the energy efficiency of the system, while nuclear has the potential to deliver its energy low-carbon and free of airborne pollutants. In the meantime, nuclear cogeneration could also supply industrial applications with steady flows of heat and power under long-term contracts. Future developments of high-temperature reactors could also unlock unique solutions for high-temperature industrial needs, among which the production of low-carbon hydrogen for energy storage (in the power or transport sectors). SNETP, through its pillar NC2I (Nuclear Cogeneration Industry Initiative[9]) currently supports the initiatives aiming at developing a demonstration reactor offering combined heat & power supply. This is reflected in the initiative's position documents (SNETP 2018a). A report prepared by OECD-NEA[10] will soon be released, providing NC2I with a methodological framework for the economic assessment of nuclear cogeneration projects. It will also offer an outlook on current cogeneration projects, estimated market size, current R&D barriers and different business model options.

4.4 Anti-corrosion solutions for materials used in ocean energy

Challenge for ocean energy. Marine environment exacerbates corrosion, a phenomenon that deteriorates the lifespan of steel structures. For energy systems like wind turbines, lifespan is a critical parameter. Indeed, compared to onshore wind power, the maintenance cost of offshore wind turbines is higher and key components (basement, gearbox…) are exposed to harsher conditions. Improving lifespan in a more hostile environment is a real challenge. Beyond wind power, improving materials to survive the sea environment is a priority for all marine energy technologies, such as wave energy converters (WEC) and tidal energy converters (TEC) (European Technology and Innovation Platform for Ocean Energy 2016). Another challenge identified in the strategic research agenda for ocean energy is the development of an artificial ageing process to test the long-term effect of corrosion on innovative materials.

Description and expected impact of the innovation. The nuclear industry has a significant experience in anti-corrosion materials: many reactors use seawater as a coolant causing evident corrosion issues; and this is only one of the many situations in which nuclear has to deal with corrosion. For some reactor designs like molten salt reactors, corrosion is a core issue as the fluids used can be even more corrosive than seawater. Research on anti-corrosion materials has started long ago in the nuclear industry and ongoing activities keep looking for innovative solutions (both for current and future

[8] www.gemini-initiative.org
[9] www.nc2i.eu
[10] OECD-NEA (forthcoming) "On the Role and Economics of Nuclear Cogeneration in a Low Carbon Energy Future"

generations of nuclear reactors) (Ferré et al. 2017; CEA 2008; Passebon 2015; DeVan and Evans 1962). The nuclear industry has also developed specific tools to simulate the action of corrosion (CEA 2008). In the end, part of the experience accumulated in the nuclear industry could certainly be useful to the sector of ocean energy.

Maturity, **barriers and drivers to transfer anti-corrosion solutions.** Anti-corrosion materials are already widely used in the nuclear industry. This is also the case of simulation tools used to test ageing materials. The maturity of these solutions should be considered as drivers to replicate the innovations from the nuclear industry to the ocean energy sector. On the other hand, some innovative solutions are still under development and some solutions may only address specific corrosion conditions: for instance, some anti-corrosion materials used in the nuclear sector are specific to high-temperature corrosion, other are specific to molten salt fluids... These innovations may not be directly transferable to the ocean energy systems (mainly subject to low temperature salt water).

Conclusion and suggestions. In the end, improving the lifespan of ocean energy systems is a key challenge in the development of this sector. Corrosion is one of the main phenomena impacting lifespan as it deteriorates the performance and reliability of these systems. Over the past decades, the nuclear sector has accumulated a significant experience in material innovation to slow and counter the effect of corrosion. It has also developed tools to simulate the impact of corrosion on materials as this phenomenon can have long-term effects. Therefore, a memorandum of understanding (MoU) between SNETP and TP Ocean to share and make the most of the nuclear expertise in terms of corrosion could be a good step towards a collaboration between the two industries. A collaboration between EERA JPNM and JP Ocean Energy could also be considered. It would open new opportunities for nuclear to spread the results of internal research and for ocean energy to improve the lifespan, the reliability and the economics of offshore energy systems.

4.5 Offer flexbility to the electricity system

Challenge for the electricity system. For a power system to function effectively, it needs to have power plants certifying that they can supply power in the event of power deviation from the expected value. This is called “back-up power”. The current increase of intermittent power plants – such as renewables – in a power system triggers new needs for back-up power:

- Balancing back-up with existing capacities in the short-term linked to variability and uncertainty of these intermittent sources in the short term.
- Building new back-up capacities in the long term able to cope with these intermittent sources.

In addition, the rising penetration of renewables also requires a reinforcement of the network resulting in supplementary costs. With an increasing high non-dispatchable renewable penetration, a key challenge is therefore to consider all back-up options while minimizing these system costs, preferably with low carbon emissions.

Description and expected impacts of the innovation. Nuclear is traditionally used as a baseload power source because as explained in section 3.3.4, this operation mode maximises the return on the high investment costs and is the easiest way technically. All this said, load following, which is a modulation of power to address the fluctuating needs of the grid, is not a new challenge for nuclear operators. In both France and Germany, operators have started researching on effective modulation techniques in the 1970s, in order to cope with the daily variation in the electricity demand. For France specifically, due to the high share of nuclear in its electricity mix, the country has been implementing load following since the 1980s. More recently, modulation have become more important with the rise of renewables in Germany (Cany 2017).

- Load following of NPPs would increase the flexibility of the system and therefore avoid the need to build new capacities.
- Load following and cooperation with renewables increase the resilience of the electricity system while keeping a low carbon electricity mix. Up to 2030, modulating nuclear to cope with deviation in the demand would save 2 to 8 % of the total CO_2 Emissions from the power market (Cany 2017).

Maturity, Drivers and Barriers of the implementation of load following. There are a couple of drivers to encourage this technique. First, the maturity of this technique seems to be already high since, as said in the previous paragraph, this practice has been implemented for decades in France and Germany. Then, there seem to have room for a more widespread use of load following, especially in France where only 40% of the nuclear reactors are contributing to load following (Cany 2017).

However, the operation of an NPP requires strict compliance with pre-determined safety measures, set to take into account the intrinsic physical properties of reactors. Reactors are designed for a maximum number of power variations during their lifetime because Load following causes more wear and tear of the components. Therefore, it is estimated that PWRs could carry out a maximum of 20 000 power deviations in the course of their 40 years of operation while EPRs could achieve 36 000 power deviations in 60 years of operation. Moreover, at the whole fleet level, limits of power deviation are linked to the reactors availability – they can't take place during maintenance and test periods. Load following can start two weeks after the start of the operation (Cany 2017).

Conclusion and suggestions. In Europe, the rising share of renewables in the electricity mix will challenge the integrity of grid. Load following would be a way to tackle this issue. As it is based on nuclear capacities, it could provide a short-term answer for the need of flexibility in the grid. But further R&D needs to be done to further improve the flexibility of nuclear reactors. This is therefore an issue to be primarily researched by SNETP and should therefore be included in the SRIA. Enhanced EU collaboration between operators could also be valuable, for instance through a coordinated load following in order to get a remuneration on capacity markets.

4.6 Life extension to meet EU climate objectives at competitive cost

Challenge for the European economy and climate. Electricity represents an increasing share of the European energy mix. The growth of electric transports, artificial intelligence and the digitalisation among others is expected to reinforce this trend in the coming years. The gross electricity generation could increase by 18 % by 2050 (Perez-Linkenheil 2017). With Europe being more and more dependent on electricity, a challenge for the competitiveness of the European Union will be to keep the electricity prices as low as possible At the same time, the EU will have to make power production cleaner to comply with its target to reduce greenhouse gas emissions by 80% until 2050 from 1990 levels (*Conclusion of the European Council* 2011).

Description and expected impact of the innovation. Life extension is the process of extending the operation of an ageing nuclear power plant beyond the time set in the initial operational license. This limit is assumed because the NPP operation provokes ageing and fatigue of the components, which constitutes a challenge for the performance and the safety of the plant. In the United States, the Nuclear Regulatory Commission (NRC), which originally licensed plants to operate for 40 years, has now approved 20-year license extensions for more than 75% of the fleet, enabling operation up to 60 years. The fleet is now moving forward with plans for a second round of license renewals (which the NRC calls "subsequent license renewals") to allow operation up to 80 years. Similar life extensions of the current European NPP fleet from 40 years to 50 years or even 60 years would result in several benefits both in economic and environmental terms.

Applied to the specific French case, a study analysed the consequences of life extension according to different scenarios (SFEN 2018). From around 75% today, it considers the reduction of the nuclear production in the French electricity mix to 50% following different timelines: 2030, 2035, 2040, 2045. The study concluded that delaying this reduction to 50% until 2045 in France – instead of 2030 – would drive the European electricity prices down by 10% over the period, as a result of the competitive production cost of nuclear. It would also enable France to save 50 billion $€_{2013}$. A large part of these savings is due to the fact that life-extended capacities limit the need for investments in new capacities.

In the study, the most "pessimistic" scenario for nuclear considers the life extension of a 22 GW total capacity up to 2030 in France and the most "optimist" one considers an extension of 42 GW up to 2045. It should be noted that to these gigawatts produced as a result of extensions, the ones produced by nuclear installations not extended also have to be taken into account to get the total amount of nuclear production. A more "extreme" case is also mentioned in the study, considering an extension of 12 GW in total until 2030. France would then become net importer of electricity. This lack of production would be balanced by investments in CCGT in France, Germany, Belgium and the United Kingdom, thus increasing GHG emissions of around 45 Mt (SFEN 2018).

More generally, life extension could support the energy transition through the electrification of currently carbonised sectors. Indeed, electricity produced through low-carbon sources such as renewables and nuclear is available in greater quantities compared with current demand. The surplus can turn out to be a value for the energy transition and help other sectors to be electrified and thus decarbonised (e.g. mobility, heating, cooling, etc.) (Davis 2018).

Conclusions & Suggestions. As the European energy mix is getting more and more electrified and as SNETP and the European Commission see low power prices as a key enabler for the prosperity of the European economy (European Commission 2014) (SNETP 2018a), SNETP needs to continue researching on nuclear power plants life extension and keep this issue on the top of the R&D priorities in the NUGENIA and SNETP roadmaps.

5 Synthesis, recommendations and action plan

5.1 Spin-in Synergies

The following table summarises the spin-in synergies previously identified and proposes in a nutshell potential steps forward for SNETP.

Challenges	Innovation & Impact	Possible steps to move forward
Nuclear Safety, Reliability of Components & competitiveness of nuclear energy	Virtual reality and Digital twins to increase the reliability of components, facilitate maintenance activities, and boost the competitiveness of nuclear	1) Liaise with the digital ETPs to meet the digital community, identify key stakeholders and eventually acknowledge their research results in implementing digital twins in power plants. 2) Discuss the respective SRAs and identify common issues of interest. 3) Coordinate joint research through either in-kind-projects within SNETP Community or EU-project to research on the previously identified common issues of interest 4) Formalise this link in the long term by signing a MoU between the platforms
Nuclear Safety, Reliability of Components & competitiveness of nuclear energy	Robotics and drones to increase the reliability of components, facilitate maintenance activities and boost the competitiveness of nuclear	1) Liaise with the euRobotics initiative, which has set up Topic Groups[11] to address applications of robotics (including space, industry, logistics, etc.), in order to support the inclusion of nuclear applications in its future SRA (post-2020) 2) Develop joint research projects with the robotics community, on identified issues of common interest 3) Formalise this link in the medium term by signing a Memorandum of Understanding between the platforms
Oversupply of electricity during peak periods (high renewable production)	Storage of the electricity produced by nuclear via PHES, hydrogen or other low-carbon storage solutions to limit the decline of NPP load factors	Carry out studies on hybrid power plants combining nuclear with hydrogen production and investigating new sites for PHES.

Challenges related to 4th generation reactors (Gen IV) were not detailed in this report. The reason for this is that no obvious synergy from the outside world was identified to facilitate the development of Gen IV. Further investigation on this point could be necessary.

[11] https://www.eu-robotics.net/sparc/topic-groups/index.html

5.2 Spin-out synergies

The following table summarises the spin-out synergies previously identified and proposes in a nutshell potential steps forward for SNETP.

Challenge for the other sector	Innovation & Impact	Possible steps to move forward
Scarce CRMs, necessary for many essential products like electric motors, batteries, micro-processors	Recovering CRM from the nuclear spent fuel	Establish a working group with EERA-JPNM on critical raw materials of interest for nuclear sector. Dialogue with the metal recycling industry to be engaged
Scarce xenon resources, a gas used by the thrusters of the satellites	Recovering xenon in the nuclear spent fuel for the benefit of the space sector	Establish a working group to analyse the economics of recovering xenon in the nuclear industry
Competitiveness and decarbonisation of the European Industry	Cogeneration to supply industry, cut CO2 emissions and store energy	Communicate effectively on the results of the GEMINI+ project, especially on the action linked to the potential industrial end-users.
Corrosion deteriorating the lifespan of steel structures	Anti-corrosion innovations developed by nuclear could be for materials used in ocean energy	Envisage a MoU between SNETP and TP Ocean to share and make the most of the nuclear expertise in terms of corrosion
Integration of renewables in the grid & security of supply	Implementing load following in NPPs to support the integration of renewables in the grid, increase its flexibility and avoid building new capacities	Inclusion of this issue in the SNETP SRIA To be considered in the NUGENIA TA3 roadmap
Limit the increase of the electricity prices in Europe and cut CO2 emissions	Life extension of NPPs to support the European economy and cut CO2 emissions	The issue is already considered in the SNETP SRIA and should continue to be within the scope of NUGENIA

In this report, the most promising spin-out innovations were identified but other potential spin-out areas can be listed like nuclear innovations serving the field of medicine.

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