European SMR pre-Partnership Reports

Workstream 1 – Market Analysis

SMR European pre-Partnership

Workstream 1

Market Analysis

Contents

ACRONYMS

Abbreviation	***Expansion***
AMR	Advanced Modular Reactor
ATF	Accident Tolerant Fuels
BWR	Boiling Water Reactor
CCGT	Combined Cycle Gas Turbine
DH	District Heat
EPZ	Emergency Planning Zone
ESG	Environmental, Social and Governance (Criteria)
ETS	Emission Trading System
FOAK	First-Of-A-Kind
GHG	Greenhouse Gas
HTGR	High Temperature Gas Reactor
LCOE	Levelised Cost Of Electricity
LFR	Lead-cooled Fast Reactor
LMFR	Liquid Metal Fast Reactor
LW-SMR	Light Water Small Modular Reactor
MSR	Molten Salt Reactor
PWR	Pressurized Water Reactor
RES	Renewable Energy Source
SFR	Sodium-cooled fast reactor
SMR	Small Modular Reactor
TRISO	TRi-structural ISOtropic particle fuel

1. Market Needs

1.1. Introduction

The current challenges facing our society can seem at times daunting. Climate change and the need for decarbonisation, along with the shifting geopolitical landscape placing emphasis on energy independence and security of supply, are a few of these challenges. This report addresses the future needs of the EU energy/power market, market size and global competitiveness in a context of high RES deployment based on existing literature and market research. It emphasises that nuclear technology and particularly small modular reactors are an integral part of the solution.

Both pushing and pulling forces support that statement. Push comes from independent climate-related publications combined with the demands of policies such as REPowerEU, highlighting the pressing need for large-scale low carbon technologies. Pull comes from the financial viability of SMRs in a range of applications, such as electricity, industrial heat, hydrogen generation and district heating. Market projections point to a significant and ongoing demand, resulting in a viable business model for European nuclear suppliers and operators. What is more, SMRs have competitive advantages over other lower carbon technologies, adding to the overall appeal. This paper illustrates that through SMR technology Europe's nuclear industry can offer policy makers' new sustainable and economically sound solutions.

1.2. Techno Economical basis for considering SMRs

Whilst an initial fleet of large nuclear power stations are already planned across Europe for construction by 2035, SMR technology could also play a large potential role in the European energy sector in supporting deployment of low carbon generation that is quicker to deploy and easier to finance,.

The estimated scale of deployment of new nuclear capabilities varies widely due to uncertainty on technology selection, regulations and the wider energy context. However, it is clear that a solution using only renewable energy sources to reduce greenhouse gas emissions presents a capability gap in terms of energy storage that could lead to a dramatic increase in the total system cost of energy when security of supply is required. This does not just extend to critical infrastructure such as hospitals, data centres but also to ensuring homes can be reliably powered 24/7 as part of a reliable energy grid. A recent study by Mckinsey found that to guarantee reliability of clean power with renewables and energy storage alone could drive the levelized cost of energy up to between $170-245/MWh unless advances are made in long term energy storage. Such advances would still leave the 'platinum standard' of 98% clean power availability at a range of $90-$105/MWh[1].

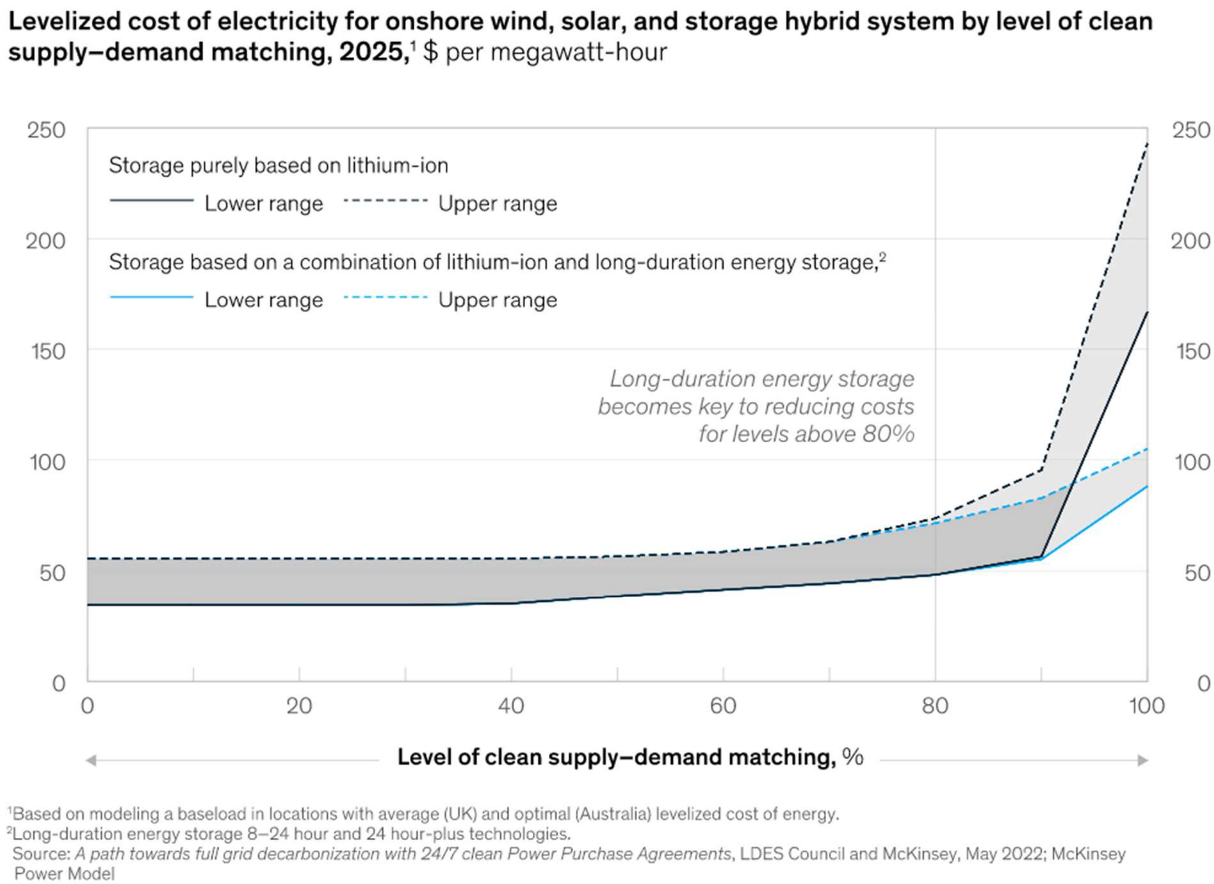

Figure 1

The recent IPCC Working Group III report adds to a growing body of acceptance that nuclear power will need to play a key role in supporting decarbonisation and maintaining security of supply[2]. Direct evidence can be seen now as countries strive to achieve energy independence and many are turning to reliable, carbon-free nuclear energy and the growing number of countries including nuclear energy in their Long-Term Climate Strategies. This renewed, strong interest offers an economic opportunity for deployment of SMR technology at scale and in doing so also presents a global export opportunity for new nuclear energy systems developed in Europe.

The techno-economic potential of SMRs relies on several important differentiators to large scale nuclear and to the capabilities of other low carbon energy generation methods.

- Reduced risk, reduced cost - The anticipated scale of production from SMR technology coupled with the smaller scale of the components themselves lends itself to a factory production methodology which can significantly reduce costs overall and minimise delays as any single component can easily be replaced. SMRs have the potential to see technology costs reduce at a faster rate than large nuclear costs for two reasons: Firstly, SMR deployment involves a higher pace and volume of reactor production. Secondly, steeper learning curve could be achieved for SMRs with their greater proportion of factory-built as these manufacturing facilities provide a more effective learning environment. A Techno-Economic Assessment performed by the UK government on SMR technology found that large nuclear has historically achieved learning rates from a single FOAK plant of 1-3%, whereas SMRs could achieve a learning rate of between 6.5% and 8% (depending on the pace of deployment). The central learning rates estimated for SMRs are more in line with the observed learning rates of industries such as CCGT (10%-22%), wind turbine production (5%-19%), shipbuilding (15%-20%) and aircraft manufacturing (18-20%) where a high proportion of construction is also factory-based[3].

- Power flexibility - SMR technology offers flexibility in power generation options, providing both electrical and thermal power for a variety of use cases. In absence of fossil fuels as both a heat source and a chemical feedstock, many critical industries will require new solutions. Whilst a range of options to decarbonise exist, they all require low carbon energy at a vast scale. The range of SMR technologies available covers a multitude of hard-to-decarbonize sectors, ranging from requirements for electrical power only to low and high temperature thermal power.
- Deployment flexibility - The smaller physical size of SMRs enables greater deployment opportunities including sites close to the points of demand. There are variable sizes and corresponding power outputs available across the SMR design landscape, ranging from designs suitable for the supply of electricity and heat on a city scale down to the decarbonisation of isolated industrial activities or the remote production of energy vectors such as hydrogen or synthetic fuels.
- Direct replacement opportunity - In many cases SMRs can support the replacement of existing fossil fuelled thermal power plants with minimal to no changes in transmission infrastructure and often within the site boundary of the replaced plant. This helps to minimise new transmission infrastructure costs, minimise land use and also supports community regeneration as a key tenet of an equitable transition. The scenario of direct replacement of fossil fuel assets serves to further highlight the complementarity of nuclear technology with renewables.
- Speed of deployment – Whilst many SMR designs are not predicted to deploy until the late 2020's at the earliest, the nature of their factory production methodologies and modular deployment enables a more rapid continued expansion following first units. With the added ability to replicate production capability once established, this unique aspect of SMR production presents the economic case for not only drastically reducing the cost of unit power but also in enabling rapid roll-out of additional capacities. The production rate can be dramatically increased through both the wholesale replication of capacity to meet demand and also the continuous improvements in factory production methods and efficiencies which can be leveraged by each factory in operation.

The cost of SMR deployment is sensitive to the cost of capital, which is based on the risk investors take. SMRs could, however, make it easier to finance new nuclear; both by reducing construction risk and by reducing the amount of finance needed for each project. It is expected that the cost of capital would reduce once the First-Of-A-Kind SMR plant is operational. Cost of capital will, in part, be a function of the policy environment and decisions made by Governments, which may influence the eventual costs. If SMRs were able in the long-run to achieve just a 1% reduction in the cost of capital this is equivalent to a roughly 11% reduction in total project financing costs[3]. Uncertainty of financing options results in a wide range of expected SMR costs. Independent assessments by the Pacific Northwest National Laboratory[4] and Minerals Council of Australia[5] give a range in the cost of installed capacity between 2600-4500 €/kW, corresponding to a LCOE range of 45-55 €/MWh (utilising average exchange rates in June 2022 of €1:$1.05 and €1:AUD$1.54). Even with a large uncertainty, the range of prices still presents an economic opportunity for SMRs against alternatives such as renewables with energy storage[1] or fossil fuels with carbon capture and storage[6].

SMR deployment may also present other qualitative impacts not factored into any financial analysis. These include improved air quality and reduced dependence on fossil fuel imports, as well as a more dispatchable form of low carbon generation relative to offshore wind, thereby enabling more efficient system-wide performance. There is also uncertainty around the feasibility and cost of the counterfactual technologies alone as part of a complete energy system.

There are a number of factors that will be critical for SMR supply chain development, including progress in harmonising licensing arrangements across Europe, governments taking a 'fleet deployment' approach, planning for modularisation early on and providing investor certainty around the volume of SMR deployment of a particular design. Consideration of the fleet approach is particularly relevant for deployment of an SMR design across multiple borders to ensure the benefits of fleet deployment and operations can be reaped by all.

1.3. Electricity Sector

1.3.1. A potential large market, in Europe and Worldwide

Key messages:

- Big market worldwide for nuclear in general. Some view that SMRs could represent 30% of it by 2050
- Europe is one of the most promising markets, and one of the first movers. There is an opportunity to repeat the success story of the wind industry.
- To meet the Paris Agreement emissions reduction path, massive electrification and decarbonisation of the electricity mix is necessary (IEA, IPCC).

There is a consensus from international organisations and agencies on the critical role for nuclear energy in order to decarbonise the electricity mix worldwide. The IAEA established that up to 800GW of Nuclear Energy will be needed by 2050 **for the electricity sector only**[7]. This is equivalent to doubling the existing capacity.

Due to their inherent qualities (smaller footprint matching a higher variety of sites, ability to decarbonise other sectors such as industry and heating, smaller financing needs), SMRs have the potential to unlock nuclear development in many markets otherwise not available to large nuclear plants.

The 2022 NEA report[8] mentions a potential of up to 21 GW by 2035. McKinsey & Company envisages between 50 and 150 GW per year[9]. In its last report, the NEA mentions a potential of 375 GW of installed capacity by 2050[10], for either supplying a centralised power grid, or to produce hydrogen via electrolysis (electricity-based process).

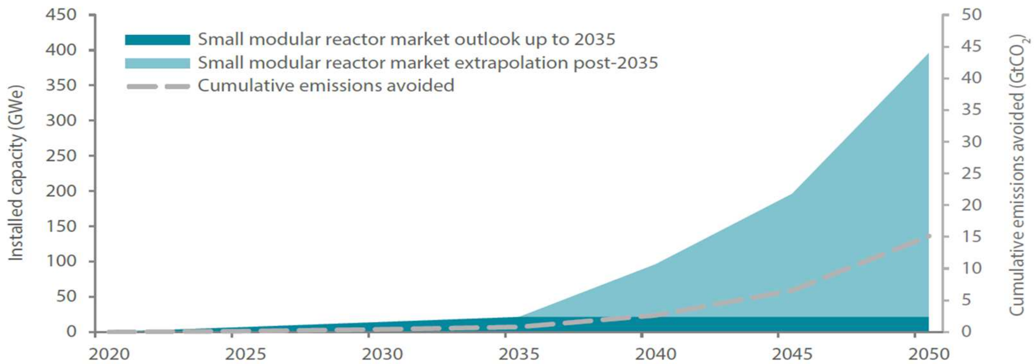

Figure 2 : SMR installed capacity worldwide and GHG emissions avoided

With 2638 TWh[11] produced in 2020, the EU electricity still represents about 11%[11,12] of global electricity needs and EU emissions roughly 10%[13] of global CO_2 emissions. With an ambition to transition to a net zero-carbon economy by 2050, with an intermediate milestone of cutting its emissions by 55% by 2030, the European Union is leading the way on the decarbonisation pathway.

Nuclear Energy is today a large part of Europe's low-carbon Generation. It has avoided the equivalent of 22Gt[14] of CO_2, six years of global EU emissions[13,14]. Meeting Europe's decarbonisation ambition will require a rapid surge in the development of all low-carbon generation. Out of the current 2638 TWh generated, 65%[11] are already low-carbon, with nuclear generation representing 675TWh[11]. With 37 years on average, the European nuclear fleet is one of the oldest in the world. Only maintaining nuclear power at the same level of generation will require to build **80GW** (Capacity today of 100GW[15], reduced to 20 by 2050, assuming 60 years lifetime).

To achieve its net-zero target by 2050, **1700 TWh**[11] **of extra low-carbon** power will be needed. This would mean more than doubling the existing renewables capacity (including hydro power). Met with nuclear, this would mean building around 200 GW of new nuclear reactors, i.e. 7 GW per year during 30 years. Though challenging, this pace has already been met by the nuclear industry.

Faced with this challenge, and taking into account security of supply, sovereignty and resilience criteria, many countries are considering, or have launched ambitious nuclear programs. Table 1 provides examples of recent announcements and commitments in Europe.

Table 1 : examples of recent announcements in Europe

Country	Policy
Belgium	In June 2023, the Belgian government and the owner of the NPPs announced an agreement to extend the lifetime of two reactors by a decade through 2035. 100 M€ over 4years promised to the Belgian Nuclear Research Center for R&D on SMRs.
Czech Republic	Czech Republic is committed to phase out coal (representing today 70% of the mix) before 2038. In March 2022, a tender was launched for building 1 nuclear power plant and option to build 3 more. In June 2022, a Request for information was launched for one FOAK SMR, with options for at least 3 more.
Estonia	Cooperation with the USA under the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology capacity-building programme.
Finland	Fortum is collaborating with EDF to jointly explore collaboration opportunities for SMR and large power plant deployment.
France	Following the France 2030 investment plan, announcement to extend the lifetime of all nuclear reactors that can be extended while ensuring safety. Announcement of plans to build six new large reactors starting in 2028 at a cost of around EUR 50 billion, with an option to build eight more by 2050. A 1 billion Euros investment (500 M€ for Nuward and 500 M€ for AMR) to develop innovative reactors, including building a small modular reactor by 2030.
Netherlands	Discussions in 2022 on the construction of two new large nuclear stations. Ongoing discussions for SMRs in the province of Limburg. Support for the development of SMRs also received funds of EUR65 million in the draft budget.
Poland	The 2020 Polish Nuclear Power Programme plans the construction of large reactors with a total capacity of between 6 GW and 9 GW. In 2022 the government agreed to the deployment of SMRs based on US technology to replace existing coal-fired co-generation plants. Private companies like Synthos, Orlen, KGHM show interest to develop SMRs.

Romania	Nuclearelectrica, state-owned nuclear operator, plans to develop SMRs in Diocesti.
Sweden	The government has agreed the removal of prohibitions in the Environmental Code to allow new reactors at new sites and to permit more reactors in operation at the same time. Vattenfall has started a feasibility for the construction of SMRs at Ringhals.
UK	Announced plans for deployment of new nuclear plant up to 24GW by 2050. Committed to provide up to £1.7 billion of direct government funding to enable one nuclear project to FID this Parliament. Investing £100 million into Sizewell C to help develop this project. Investing £210 million to develop Small Modular Reactors with Rolls Royce. Announced a £120 million Future Nuclear Enabling Fund to progress new nuclear.

At the moment, despite a large potential market and many design developments, there are few SMRs in construction worldwide, none in western countries. Europe has a unique opportunity to repeat the success achieved in the offshore wind branch. As an early mover on this technology, Europe was able to shape the market and secure a leadership position for its supply chain. Based on a strong nuclear basis, with robust fundamentals underpinning a potential large market, Europe is well positioned to write a new success story, contributing to moving to a fair transition to a decarbonised economy.

1.3.2. Market potential for SMRs

The potential European market for nuclear and SMRs represents large and mature opportunities: around **3420 TWh of low-carbon electricity is needed by 2050**[11]. It is considered that one third of this electricity should come from nuclear energy if Europe wants to reach its net zero goal. **SMRs could represent 30%** on the installed nuclear fleet, meaning more than **40 GWe**.

1.4. Industrial Heat

1.4.1. Market Overview

The industrial sector is indispensable to Europe's economy and needs to reach climate neutrality by 2050, while maintaining, and ideally improving, its global competitiveness.

This section will focus on reduction of CO_2 emissions in the energy-intensive industries, which constitute the bulk of the industrial GHG emissions.

Figure 3[16] shows the share of emissions of industrial sectors in the EU Emissions Trading System. The sectors of iron and steel, refineries, cement, petrochemicals, and fertilizers account for over 70% of industrial emissions in the EU ETS.

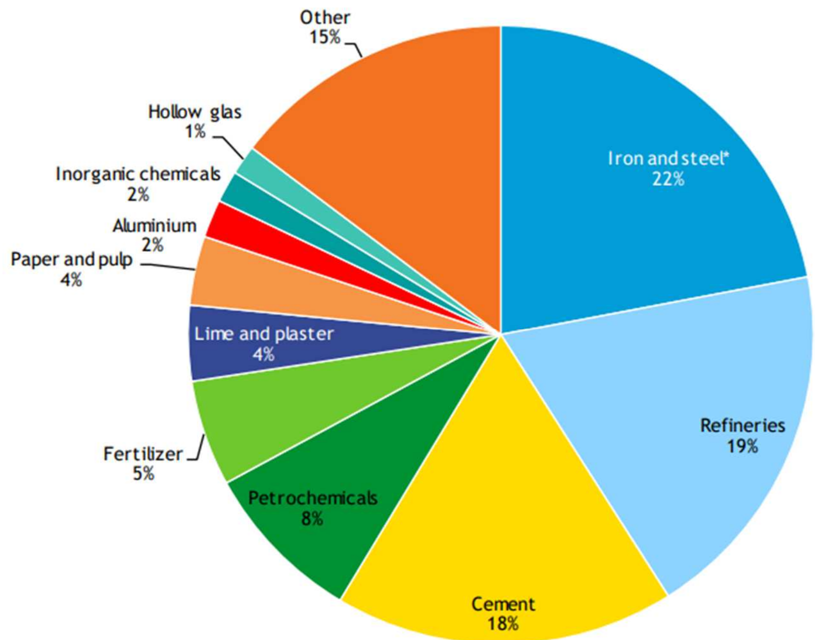

Figure 3 : Share of CO_2 emissions in the total industrial CO_2 emissions in the EU ETS in 2018

While CO_2 emissions of energy-intensive industries have fallen significantly since 1990, Figure 4[16] shows that the emissions of industries participating in the EU ETS are nearly flat since 2008. In fact, energy efficiency gains and corresponding CO_2 emission reductions in industrial processes have been offset by a continuous increase in industrial production.

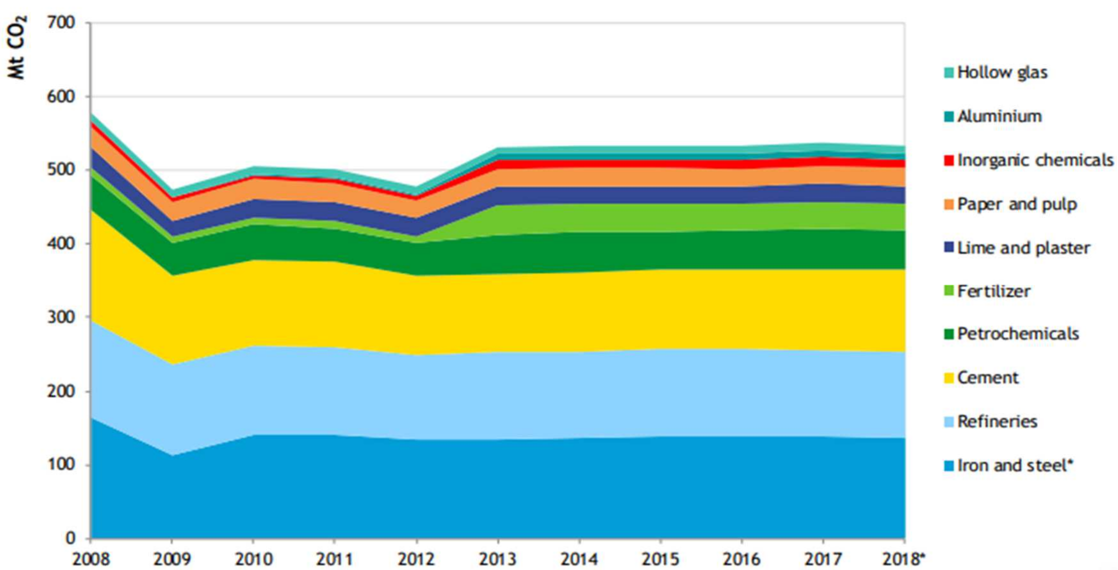

Figure 4 : CO_2 emissions in the EU ETS from the energy-intensive industries, EU27, 2008-2018

To meet climate targets, the above-mentioned energy-intensive industries need to remove nearly 550 million tons of CO_2 from their annual emissions by 2050. This is almost 20% of the EU total CO_2 emissions in 2019, hence highlighting the magnitude of the challenge.

In terms of energy consumption, Figure 5[17] depicts the industrial heat demand in the EU27 by temperature range and sector in 2009 (year from which consumption has remained more or less constant). Numbers show that 55% of industrial heat demand is high temperature heat (>400°C), 19% is medium temperature heat (100-400°C) and 26% is low temperature heat (<100°C). The iron and steel, non-metallic minerals, and chemicals sectors have the largest heat demands and also the largest high-temperature heat demands. Total heat demand amounts to almost **1250 TWh**.

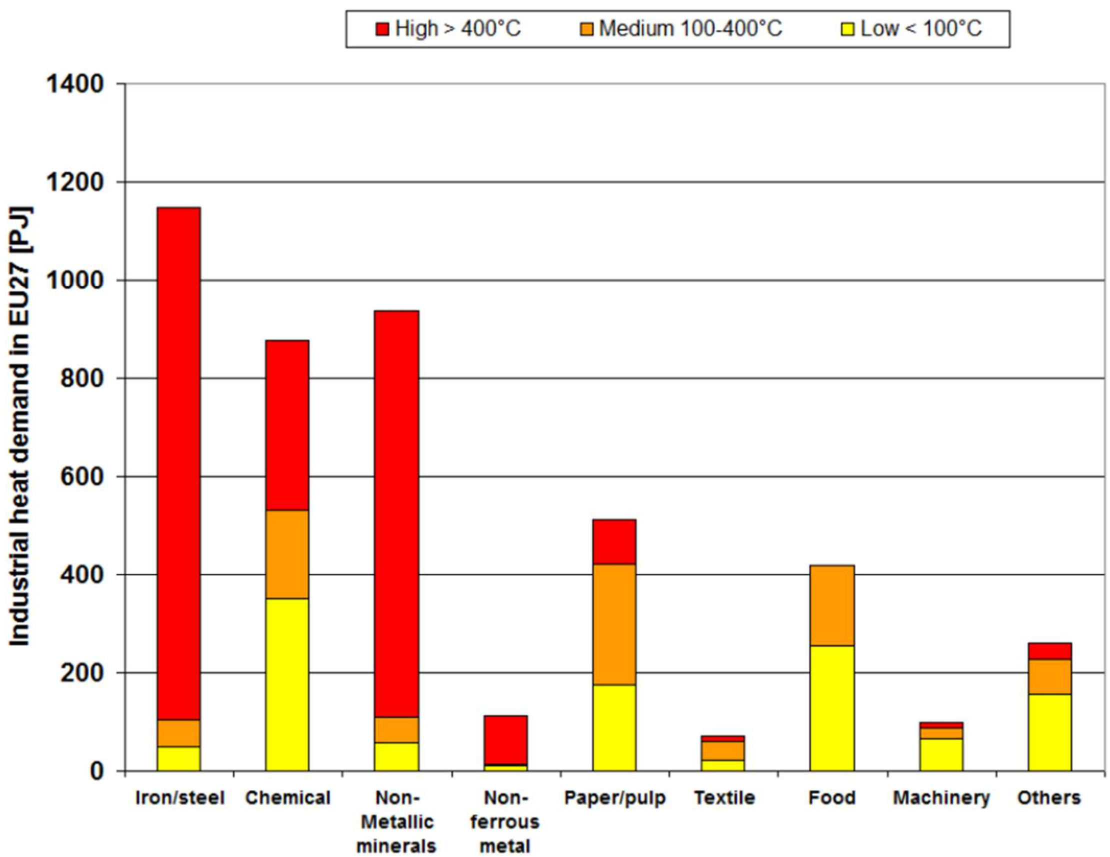

Figure 5 - Industrial heat demand in the EU27 by temperature range and sector (2009).

Many industrial companies and high energy users have identified the potential for SMRs to provide affordable low carbon energy with minimal land usage and with the high availability factors required to economically support their industrial operations. Many such industrial projects are currently in development. Examples of industrial companies who have made public their interest in the use of nuclear energy include Synthos Green Energy, PKN Orlen and KGHM in Poland and Dow, Arcelor Mittal and Microsoft in USA.

1.4.2. Market Potential for SMRs

A country-by-country analysis of the most suitable industrial sites in Europe has been performed[18], using relevant indicators such as nuclear industry maturity and appetite, co-generation potential, heat demand, and available infrastructure.

Figure 6 shows the heat market potential of selected countries. Early adopters' countries are not systematically countries with the largest absolute co-generation potential. Nevertheless, Poland, UK, and Finland stand out globally on both appetite for demonstration and overall market potential.

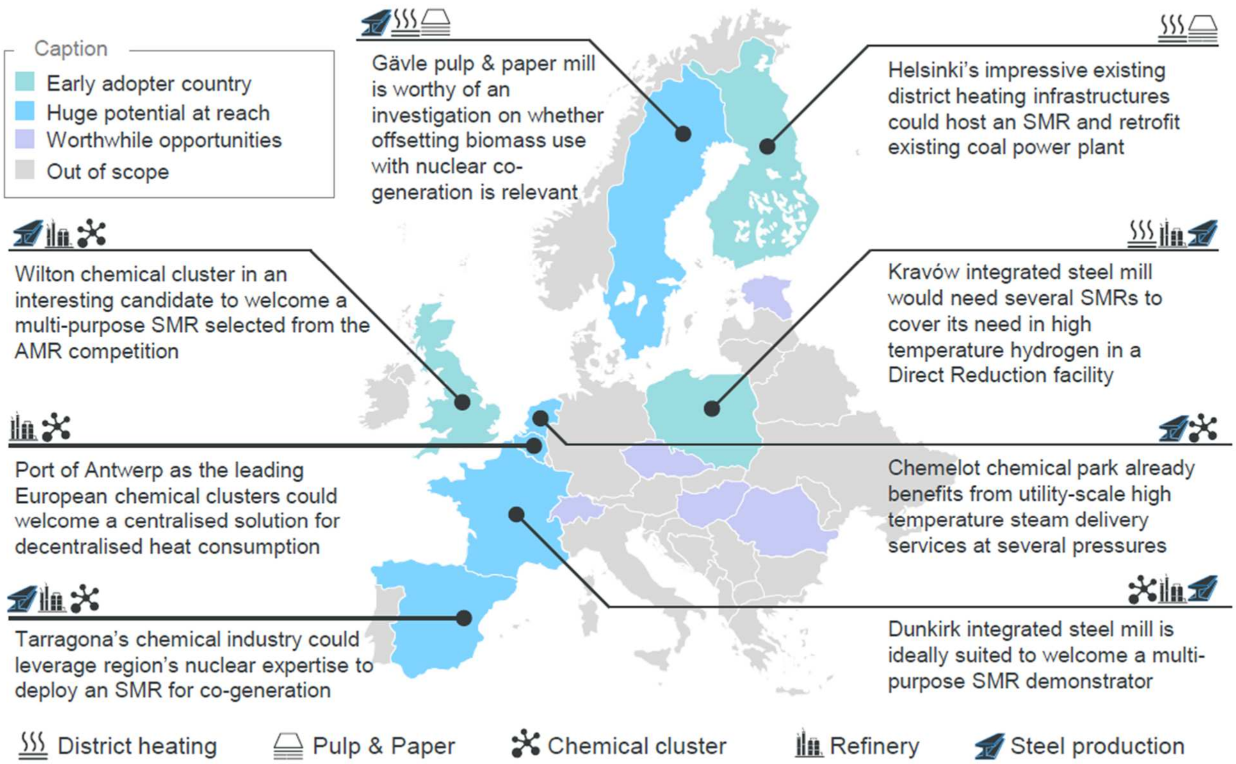

Figure 6 - European heat global market potential with illustrative examples of the diverse opportunities

The potential European market for SMRs is significant, with a total heat demand of **1250 TWh** a year (see chapter 4.1). It is considered that 10% of the low-to-medium (<400°C) heat demand should come from nuclear energy if Europe wants to reach its net zero goal. Knowing the difficulties to site a large nuclear plant close to industrial sites, most of this nuclear energy should come from SMRs, installed mainly in the countries highlighted on Figure 6. It gives an installed capacity of **7 GWth**.

Remark : this number may seem low, but it is considered that the industry will be also fed by hydrogen, which will be partly of nuclear origin (see next chapter).

1.5. Hydrogen

1.5.1. Market overview

In 2018, 457 hydrogen production sites have been identified to be in operation in Europe. The total production coming from these facilities was around 11.5 Mt per year. Of this, 9% was produced with low-carbon methods and 7% were produced as a by-product of other processes. In reality, less than 1% of the hydrogen in Europe was produced using dedicated low-carbon methods.

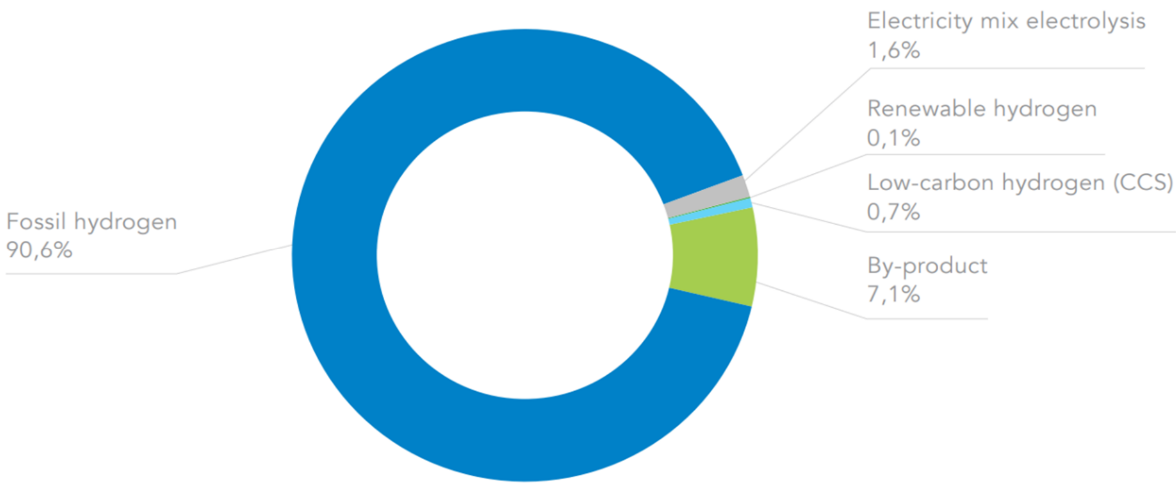

Figure 7 : Hydrogen generation capacity by technology (2018)[19]

Regarding demand, in 2018 it was estimated at around 8.3 Mt with the biggest share, 45%, going to petroleum refining followed by the ammonia industry with 34%. Emerging "decarbonisation" applications, like transport, account for less than 0.1% of the market.

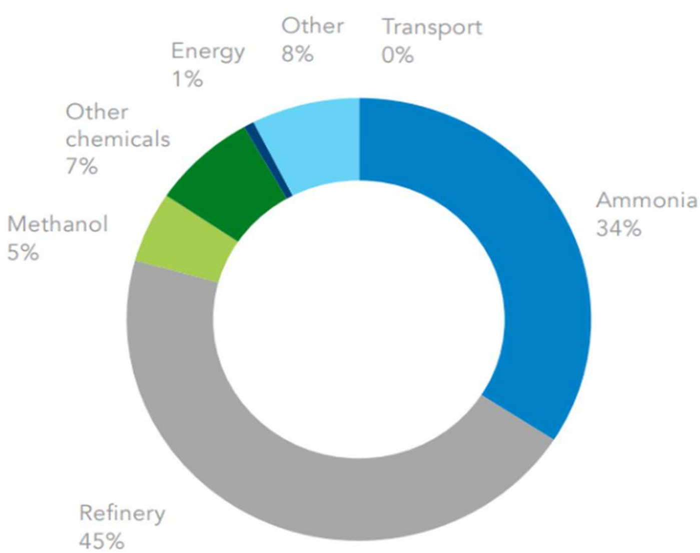

Figure 8 Total demand for hydrogen in 2018 by application[19]

1.5.2. Market Potential for SMRs

The REPowerEU plan recently introduced by the Commission sets a target of **20Mt** of renewable hydrogen use by 2030, a 3-fold increase when compared with the Fit for 55 program. Refining and ammonia are still predicted to take a big share of the hydrogen demand but other uses are now also considered, as depicted in the chart below.

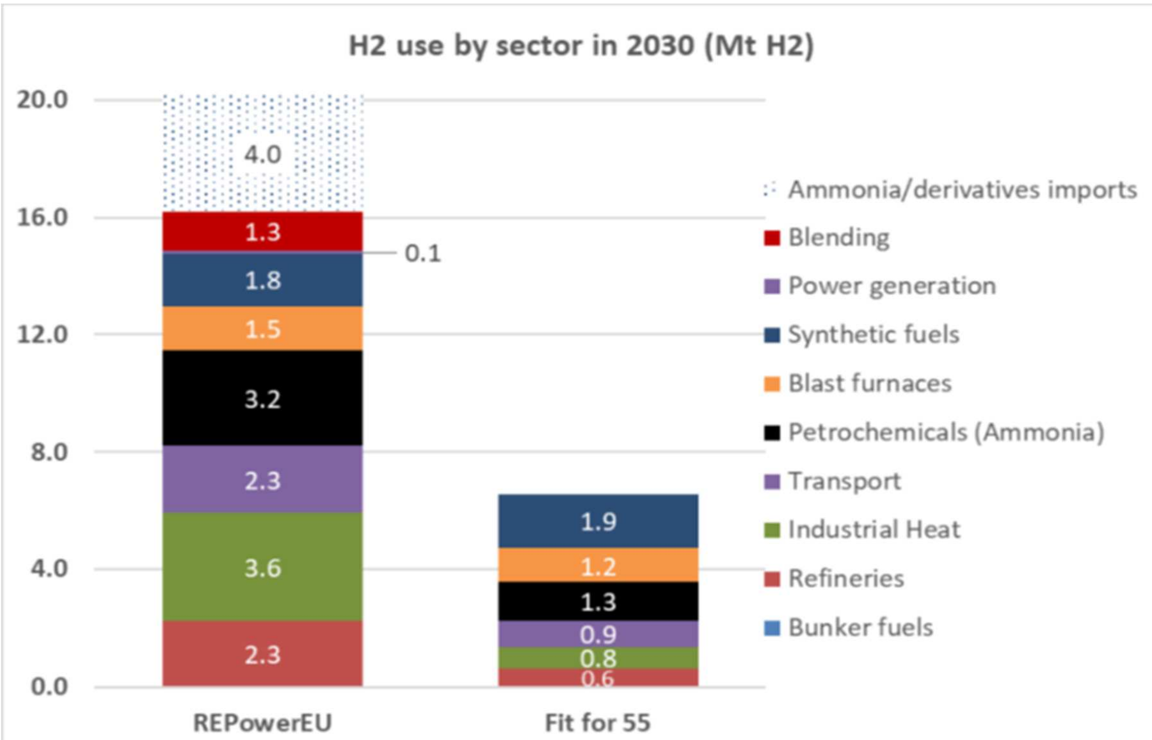

Figure 9 : Hydrogen use in Europe by 2030[20]

Most of these activities, such as ammonia production, synthetic fuel production and refining, will be able to benefit not only from direct hydrogen production from SMRs but also from electricity and heat production.

The potential European market for SMRs is huge. It is expected that by 2050, the use of hydrogen will double compared to 2030. The production of 40 Mt hydrogen is equivalent to **2000 TWh** of clean electricity. It is considered that 15% of this hydrogen demand will come from SMRs if Europe wants to reach its net zero goal. Considering that these SMRs will be used 25% of the time to produce electricity for the grid, the installed capacity would be **50 GWe**.

1.6. District Heating

1.6.1. Market overview

Based on a rough overview[21,22,23], there is currently over 300 000 MWth of district heating (DH) capacity in the 14 EU countries with the largest share of DH, producing together **500 TWh** of heat a year. Of this heat, over 70% is still produced by fossil fuels. This means that roughly 350 TWh of annual heat production must be replaced with CO_2-free alternatives. If we are to believe the current EU plans for DH[24], the size of the potential market might expand even further in the coming years.

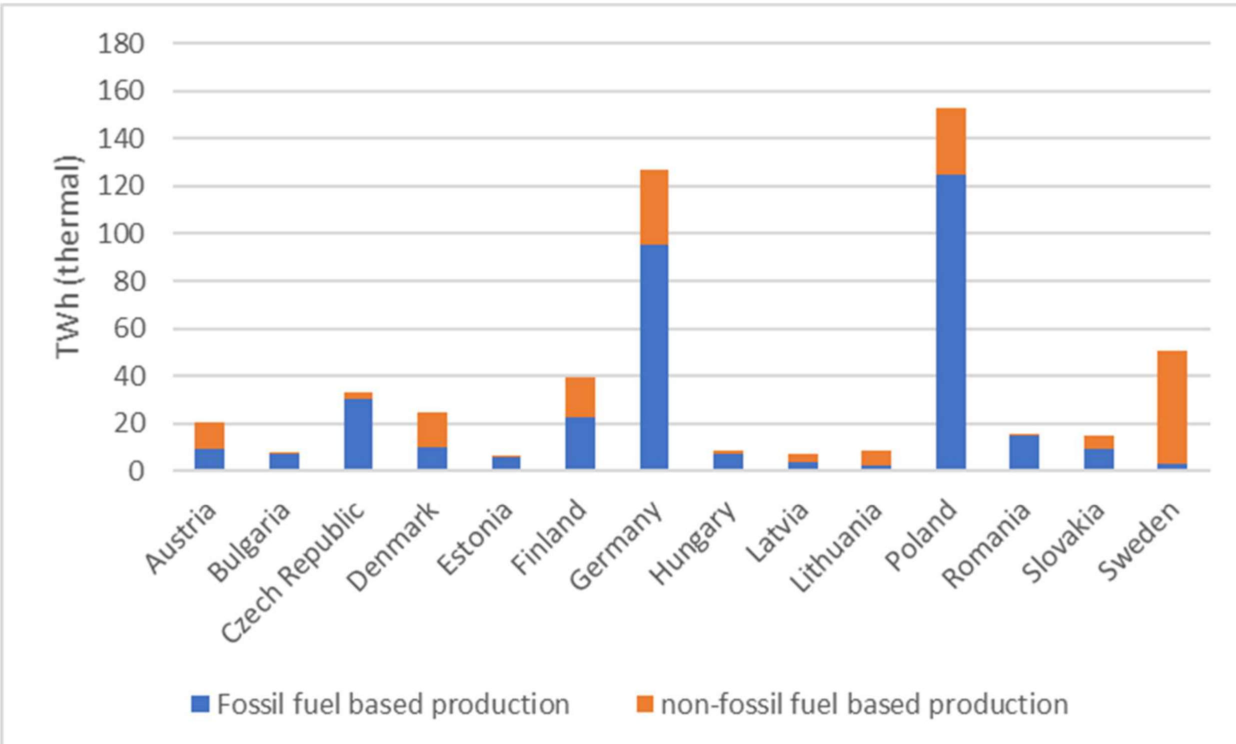

Figure 10. Approximate District heating production based on the latest data available from references 32-34 in the 14 EU countries with the largest share of DH of the overall heating needs

1.6.2. Market potential for SMRs

The market size is not directly considerable as district heating is extremely location based and the countries considered have anywhere between tens to thousands of networks with a wide variety in their total heating needs, but there should still be plenty of markets where SMRs could gain enough full load hours to be economically valid options as cogeneration or pure heating plants. A study made by the finish research centre (VTT), for example, presumes that even with the overall fairly small networks in Finland, there would still be room for SMRs in over 10 networks, if there are designs smaller than 50 MWth suitable for this use[25]. Depending on the sizes of SMRs available, availability of other options such as waste heat, etc. this would easily mean potentially hundreds of SMRs providing heat through DH networks. Based on further work from VTT, SMR DH could also potentially be one of the cheapest sources of generating district heating and thus very competitive.

So, the potential market for SMRs is significant, with more than 500 TWh a year of low carbon heat demand. It is considered that 10% of this market should be supplied with nuclear energy if Europe wants to reach its net zero goal. Knowing the difficulties to site a large nuclear plant close to cities, most of this nuclear energy should come from SMRs. It gives an installed capacity of **6 GWth**.

1.7. Scenarios for SMR deployment

1.7.1. Market potential summary

Europe has a big potential market for nuclear energy and SMRs due to its ambition to transition to a zero-carbon emission economy by 2050. International organisations and agencies agree that nuclear energy is critical to decarbonise the electricity mix worldwide, with the potential to reach up to 800GW of installed capacity by 2050. The European market for nuclear and SMRs represents large opportunities, with 1700 TWh of extra low-carbon electricity and a total low-carbon electricity production of 3420 TWh by 2050. Europe has the potential to lead the way in SMR development and benefit from the success story of the wind industry.

SMRs may also enable the decarbonization the energy-intensive industries in Europe, which account for over 70% of industrial emissions in the EU ETS. SMRs are particularly suited for industrial applications due to their size compatibility and the high operating temperatures that can provide process heat to the industry. Analysis of the most suitable industrial sites in Europe has identified Poland, UK, and Finland as early adopter countries due to their appetite for demonstration and overall market potential. Up to 45% of the EU27 industrial heat demand (1250 TWh a year) is low to medium temperature and could be directly decarbonized thanks to SMR technology, saving more than 200 million tons of CO_2 annually.

In Europe in 2018, 11.5 Mt of hydrogen was produced from 457 production sites, with less than 1% of it being produced using dedicated low-carbon methods. Demand for hydrogen has been estimated at 8.3Mt, mainly going to petroleum refining and ammonia production. The European Commission has set a target of 20Mt of renewable hydrogen use by 2030. Activities such as ammonia production, refining and power generation will benefit from direct hydrogen production from SMRs and electricity/heat production.

District heating plants in 14 EU countries produce 500 TWh of heat a year, with 60% of this heat still produced by fossil fuels and outlining the potential for SMR designs to provide DH in tens of networks. SMR DH could potentially be one of the cheapest sources of district heating and thus be very competitive in the market.

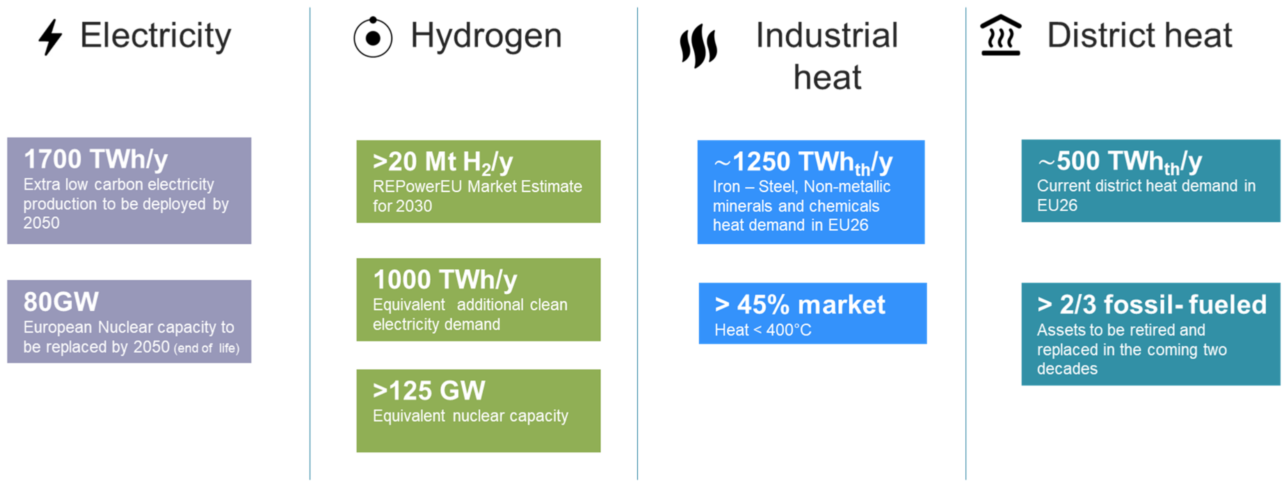

Figure 11 : key findings from the market analysis

1.7.2. Three scenarios for SMRs deployment

Based on the inputs collected in chapters 1.3 to 1.6, three scenarios are proposed to quantify the future SMR market and its contribution to reaching net zero carbon in Europe.

- Current projection (CP) : projection based on current project pipeline if little is done to boost market. It is based on the credible projects that have been announced so far for 2030-35 (see figure 12), with an assumption that half of these projects will reach completion. After 2035, new projects start regularly but without inflexion point.
- Boosted deployment (BD) : through the support of the Partnership, more projects reaches completion and a clear inflexion point is visible in 2035.
- Net zero 2050 (NZ) : a retro-planned ambitious market is proposed to be consistent with the need of low-carbon energy required to fully decarbonize Europe's economy by 2050.

Moreover, it is projected that 75% of the deployed SMRs are Light Water Reactors. The remaining 25% are different types of Advanced Modular Reactors, used for improved fuel cycle sustainability, high-temperature hydrogen production or high-temperature (>250°C) industrial heat. More details on the assumptions taken in the three scenarios are given in Table 2.

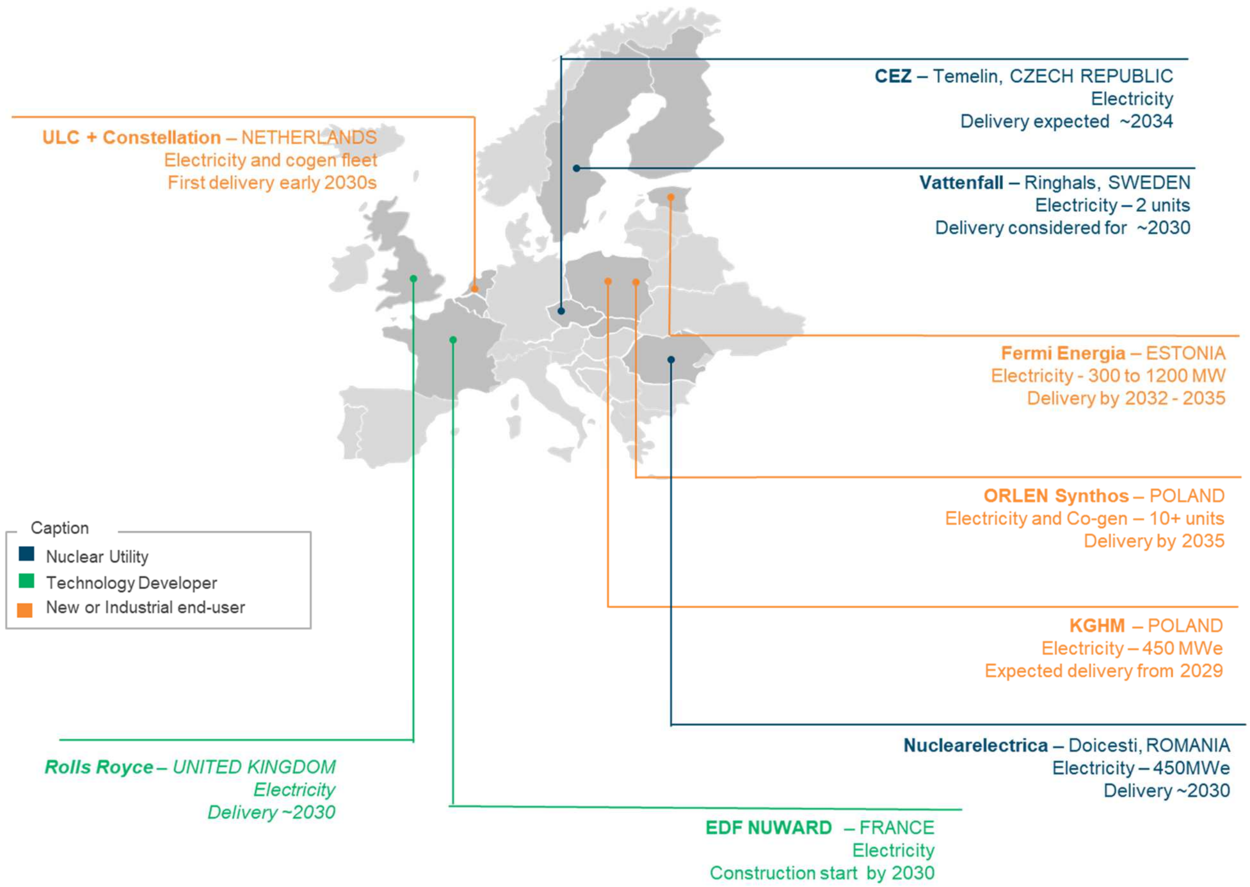

Figure 12 : Current project pipelines for 2035 delivery

Table 2 : assumptions for the three scenarios

	Current Projection	Boosted Deployment	Net Zero 2050	
Electricity	• 50% of currently identified projects are delivered by 2035 • Electricity is the main driver of development • Pace of SMR deployment limited to 800MW/year due to supply chain capacity • Hydrogen starts later but economic proficiency limits deployment to 1% of total market	• New projects initiated through the Partnership creates scalable deployment in the period 2035 - 2040 • Supply chain and licensing bottlenecks are solved • Large trickle-down effect on European economy due to volume order and supply chain retooling • Improved cost competitiveness thanks to "contract program" which enables hydrogen market	1/3 of 2050 EU electricity market (3420TWh, see ch. 3.2) comes from nuclear (30% SMR - 70% large scale)	40 GWe
Hydrogen[1]			15% of EU 2050 hydrogen market (2000TWh, see ch. 5.2)	50 GWe
Combined Heat & Power - Industry	• Deployment limited to few pilot projects in Eastern Europe industry but never at scale	• Successful pilot projects creates appetite from larger markets (20 big industrial sites even in most nuclear countries)	10% of <400°C Industrial Heat demand (45% of 1250TWh, see ch. 4.2)	7 GWth
District heating	• Pilot plant in Finland and Czech Republic but no upscale	• Around 10 sites are developed across Europe between 2035 - 2045	10% of EU 2050 DH market (500TWh, see ch. 6.1)	6 GWth

Considering these assumptions, the SMR installed capacity[2] in the three scenarios is shown on Figure 13. In 2050, there are more than 15, 50 and 100 GW of installed capacity[3] in the CP, BD and NZ scenarios respectively. The corresponding yearly energy generation is shown on Figure 14.

[1] It is considered that the SMRs dedicated to hydrogen production supply electricity to the grid during 25% of the time to improve grid flexibility.
[2] In GWe for electricity and hydrogen ; in GWth for industrial heat and district heat.
[3] 75, 250 and 500 SMRs with an average output of 200 MW for example.

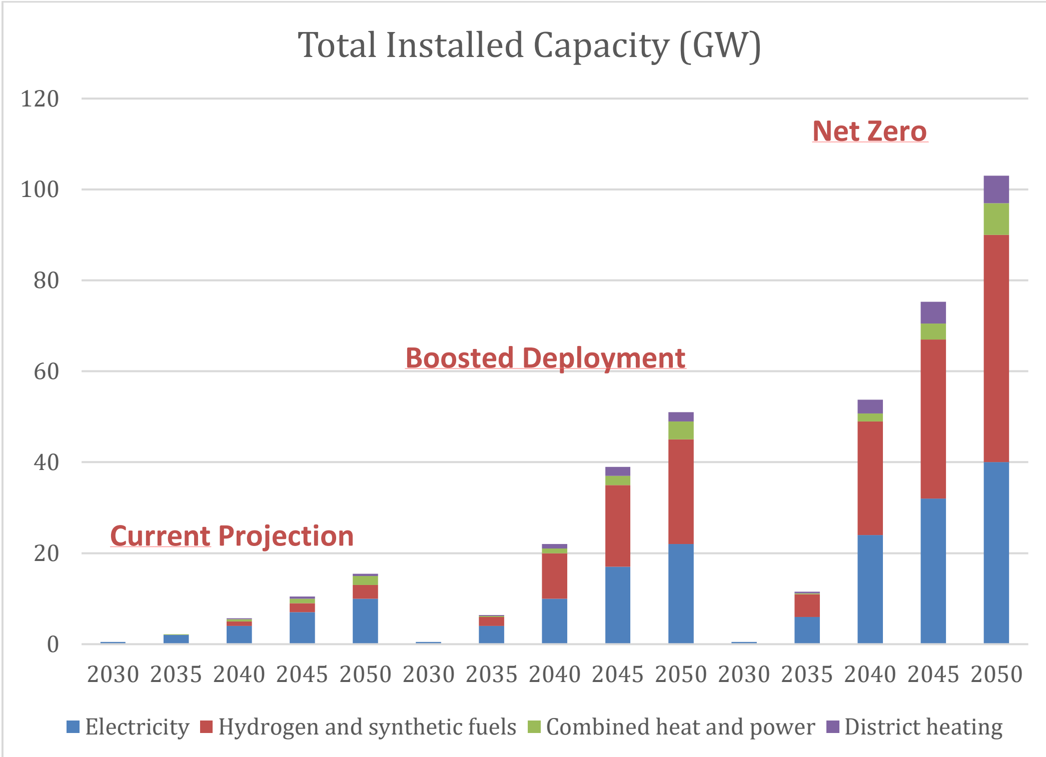

Figure 13 : installed capacity between 2030 and 2050 for the three scenarios

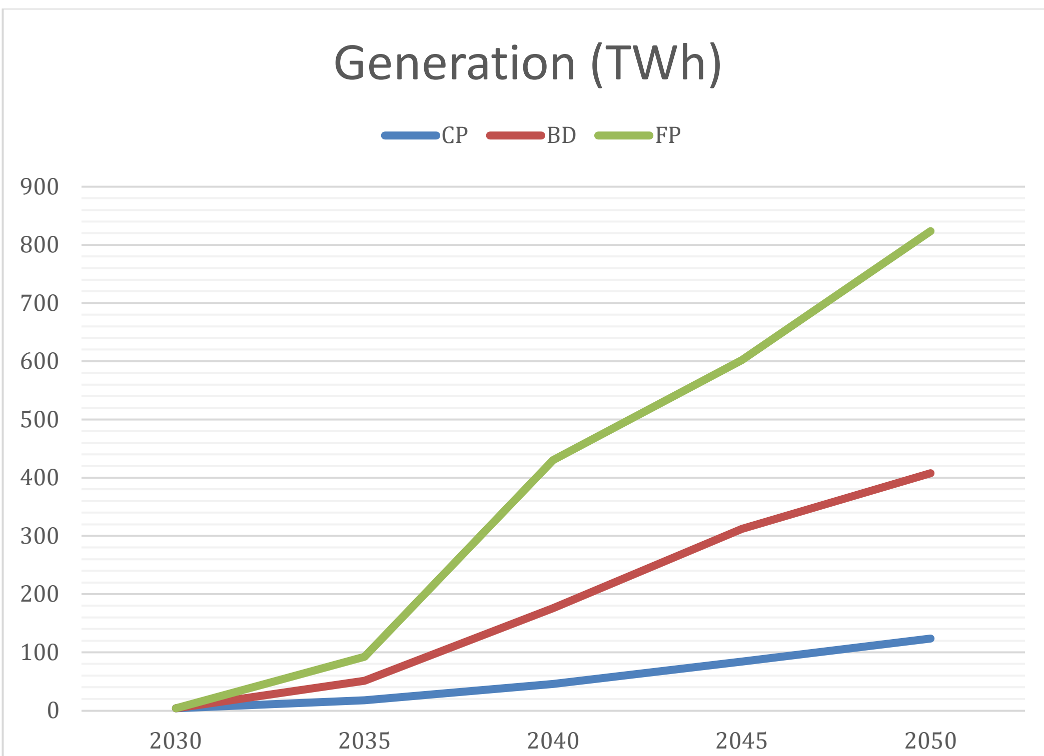

Figure 14 : yearly energy generation for the three scenarios

2. User requests

2.1. Introduction

Several operators and industrials have expressed interest in SMRs as a technology to replace coal plants and decarbonize assets/processes. This document is aiming at identifying the range of potential users of SMRs, i.e., EU industrial sectors that could benefit from SMR technology for decarbonization purpose, their requests for specific applications, and the criteria and specifications for SMRs to meet these requests.

The information needed for this assessment has been collected through literature analysis and answers to surveys sent to Member States representatives and nuclear fora.

It should be noted that electrification of uses is a straightforward way of decarbonization, provided that the grid is fed with low-carbon electricity. This is clearly a part of the path to a low carbon economy and this should be promoted for the public and for the industries. Requests from the electricity industry is discussed in chapter 2.2.

An additional way of decarbonizing the economy is through the production of molecule, i.e. hydrogen and e-fuels. This is dealt in chapter 2.3.

In some cases, and particularly when electrification is not an option, the production of heat for district heating and for industries is an option to be considered. Production of heat is discussed in chapter 2.4.

Chapter 2.5 discusses the vicinity request.

The answers from the members states and nuclear fora to the survey produced for this assessment are summarized in chapter 2.6 and are detailed in Appendix A.

The way forward is discussed in chapter 2.7.

2.2. Electricity industry

SMRs used for electricity production will in most cases[4] be connected to the European grid. Some of them will be requested to operate baseload and will be mainly requested to have a high availability. But, with an increased share of intermittent renewables, more SMRs will be requested to be flexible. This flexibility can be provided by varying the power of the reactor, and hence the electricity output. But other possibilities exist such as storing the heat provided by the reactor for further use when the electricity demand is high or by using the heat for another purpose than electricity during low demand (cogeneration).

Regardless of how the power output flexibility is provided, SMRs shall satisfy the grid requirements imposed by the European grid code (ENTSO-E) and by the national transmission system operator of the considered country.

The European Utility Requirements on availability and flexibility of SMRs can be considered as average specifications, to be adapted on a case-by-case basis, that includes requirements on :

- an average annual availability factor greater than 90% over its lifetime;
- the possibility to implement scheduled and unscheduled load variations during 90% of the whole fuel cycle;

[4] Areas isolated from the European grid would be exceptions. On the other hand, this is to be considered for deployment outside Europe.

- the ability to change the electric output at a rate of at least 3% of the rated power per minute, between 100% of the rated power and a minimum operating level of the reactor[26].

Regarding the deployment model for SMRs dedicated to electricity production, multiple units on one site will be the preferred option from a technical and economical point of view. Multiple units decreases the costs associated to licensing and on-site construction while allowing auxiliary facilities to be shared between them. In addition, the reduction in the number of nuclear sites will allow for better social acceptance. However, the configuration of the European grid at the time of deployment of SMRs may require small isolated power plants that could be filled by stand-alone SMRs.

The focus for SMRs deployment will first be to replace fossil-fuel units. It will be the most efficient way to decrease GHG emissions while allowing to reuse existing facilities such as grid connections, water treatment and cooling systems. Steam turbines could also be reused in some cases.

2.3. Hydrogen and e-fuel production

Low-carbon hydrogen can be produced using nuclear energy by different processes, the main being :

- water (or low-temperature) electrolysis, where electricity is used to split water into hydrogen and oxygen;
- steam (or high-temperature) electrolysis, where electricity is used to split steam water at a temperature between 600 and 1000°C;
- thermochemical water splitting, where only heat (at 600-900°C) is used to produce hydrogen from water steam[27].

Regarding water electrolysis, the two biggest impacts on the life cycle costs of hydrogen are cost of electricity and CAPEX. The advantages for SMRs to be used for hydrogen production are to provide affordable electricity and to have a high availability, hence high full load hours for the electrolysers, thereby decreasing the impact of CAPEX on hydrogen cost . Additionally, being able to provide electricity to the electrolysers directly, i.e. without using (and paying for) the grid will be an asset[28].

If steam electrolysis is envisaged, the SMR is also requested to provide heat. SMRs with high-temperature outlet (such as HTGR, MSR and LMFR) are favourable. Nevertheless, steam electrolysis using heat from a LW SMR, while less efficient, is also possible[18,30].

For thermochemical water splitting, as the unique energy source is heat, only high-temperature SMRs are considered. See the example of the sulfur-iodine cycle on the figure below.

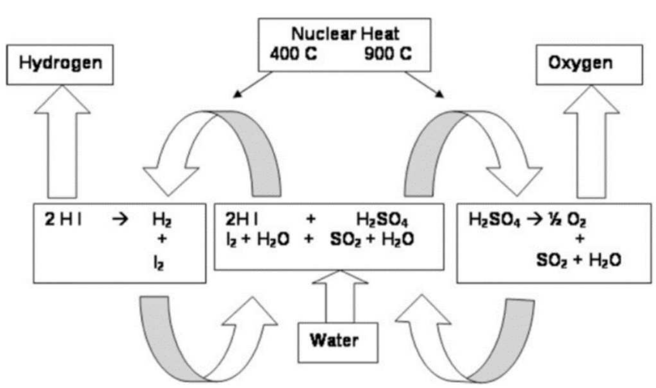

Figure 15 : the sulfur-iodine thermochemical cycle for hydrogen production

In both cases, SMRs will be requested to be close to the hydrogen production sites in order to be able to provide heat with low losses.

Once hydrogen has been produced, different types of e-fuels can be produced using carbon dioxide (e-methane, e-methanol, e-crude) or nitrogen (ammonia). This process also requires electricity and/or heat.

In any case, the preferred deployment model will be to have SMRs close to the hydrogen production plants in order to provide electricity and/or heat in an efficient way. The power of the SMRs will have to match the hydrogen production plant needs, i.e. hundreds of MWth. Cogeneration of hydrogen and electricity is to be considered as it allows to help ensuring the electricity supply by lowering/stopping hydrogen production during peak electricity demand.

2.4. Heat production

Industries generally require the supply of heat. Considering the heat requirements, the main industrial sectors to be considered are (see Figure 16):

- Low-temperature (<250°C)– district heating, paper and pulp industry.
- Medium-temperature (mainly <550°C) – refineries, soda ash production and chemical industry clusters.
- High-temperature (mainly >1000°C) – non-ferrous alloys, steel, lime and cement production.

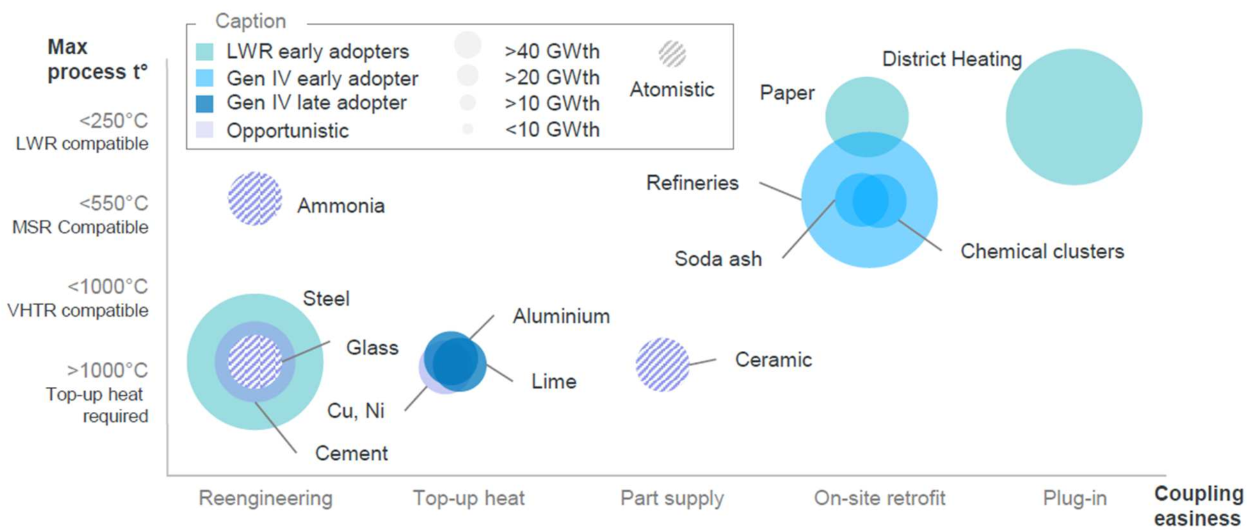

Figure 16: Industrial sectors affinity with SMR-based co-generation[18]

Ceramic, glass and ammonia (fertilizers) industries should also be considered but the average size of individual plants are relatively small, requiring less than 50 MWth. Concerning ammonia production, the main endothermic process is the production of hydrogen through steam methane reforming.

There are generally few energy-intensive industries that require heat between 600 and 1000°C. one exception is hydrogen production, which is discussed in chapter 2.3.

SMRs will have to be located close to the industries requiring heat, matching the needs of one customer, or several customers when possible (e.g. a chemistry industry cluster). Redundancy may be required by industries in some cases, when stopping production is impossible for economic or security reasons.

2.4.1. Low-temperature heat industries

District heating plants (80-130°C) and pulp and paper industry (100-180°C) require low-temperature heat that can be delivered by a LW-SMR. In average the size of one site is such that it requires less than 100 MWth. The few largest district heating plants require several hundred MWth[25].

A specificity of district heating plants is a highly seasonal dependency of the heat demand. Cogeneration may be a preferred option in order to increase the production of the second product (e.g. electricity) when the heat demand is low (summertime). Another possibility is to complement the SMR by other low-carbon sources (e.g. biomass) during peak demand. A storage of e-fuel produced during summer could be an option. This issue is less important for pulp plants.

Rem.: District heating can also be provided through heat pumps, consuming only electricity, if a sufficient heat source is present.

2.4.2. Medium-temperature heat industries

Refineries, soda ash plants and chemical industry clusters generally require heat at temperatures above 250°C but rarely above 550°C. With average plant heat consumptions of a few hundred MWth per site, these industries are good candidates to host generation 4 SMRs such as LMFR, MSR and HTGR. Such reactors are able to provide the heat at the requested temperatures while LW-SMRs should be complemented by other low-carbon energy sources or electrically add the energy necessary to reach the requested temperature.

For instance, an analysis made for the Polish chemical industry indicates that a nuclear power plant should provide steam at 540°C/13,6MPa and have a thermal power of 165 MWth[31].

2.4.3. High-temperature heat industries

These industries (iron and steel, non-ferrous alloys, lime, cement) require heat at or above 1000°C. In a near term, no nuclear reactor will be able to supply heat above 1000°C. But SMRs can provide pre-heat, complemented by SMR-powered hydrogen or e-fuel, electrification or other low-carbon heating technology. The steel industry, which is a very large energy consumer, is particularly suited to heat and hydrogen from nuclear origin when using Direct Reduced Iron method.

2.5. Vicinity request

Except when used to power the grid, SMRs will be located close to consumers, i.e. district heating plants and hence cities, hydrogen production plants, industries, … This has safety implications that need to be addressed.

In addition to have a high level of safety, SMRs will need to ensure that, even in the worst case scenario, accidents will not lead to the need of evacuating workers of the adjacent industrial plant or inhabitants. The emergency planning zone shall be as small as possible, ideally limited to the SMR site boundary.

Moreover, threats caused by the adjacent industrial plants shall be considered in the design of the SMR. Particularly, the SMR shall be able to resist fire, explosions, toxic and corrosive gases, … that could be caused by an adjacent industrial site.

2.6. Answers from the members states and nuclear fora to the survey

A summary of the answers is given in Table 3. Only 8 answers have been received so far. Once the Partnership is officially launched, efforts will be done to receive the answers from more states. The detailed surveys and answers can be found in Appendix A.

	Czech R.	**Finland**	**Hungary**	**Lithuania**	**Poland**	**Spain**	**Sweden**	**Türkiye**
Answer by	MS	NF	NF	NF	MS	NF	NF	MS
Consider nuclear	Yes	Yes	Yes	No	Yes	No	Yes	Yes
Consider SMRs	Yes	Yes	No	No	No	No	Yes	Yes
Envisage SMRs	-	-	Yes	Yes	Yes	No	-	-
Expected capabilities	E, DH, IH, H_2	E, DH, H_2	E, DH	E, DH	E, DH, IH	-	E, DH, IH, H_2	E, DH, IH, H_2

MS : Member State – NF : Nuclear Forum

E : electricity – DH : district heat – IH : industrial heat – H_2 : hydrogen

Table 3 : Summary of the main answers to the survey

2.7. Conclusion and way forward

From the answers received from Member States and Nuclear fora, it is clear that there is an interest for SMRs as a mean of energy production. All the Members States currently relying on, or showing interest for, nuclear energy should be consulted. This will be done in the next phase of the European SMR Pre-Partnership.

This document has defined some high-level user requirements for SMRs to be used for electricity, hydrogen and heat production. These requirements should be detailed further through consulting potential stakeholders such as national grid operators and energy-intensive industries[5]. This will be done in the next phase of the European SMR Pre-Partnership.

[5] A survey has been prepared. See Appendix B.

3. Small Modular Reactors in a sustainable economy

3.1. Introduction

Over recent years, the question of whether nuclear energy should be considered as a sustainable energy source was at the heart of the EU debate, due to the long-awaited inclusion of nuclear in the EU Taxonomy. Under the Sustainable Finance Complementary Climate Delegated Act , which has been published in the Official Journal on 15 July 2022 and entered into force in January 2023, it was considered that there is a role for private investments in nuclear activities in the energy transition and that nuclear energy activities could be classified under certain conditions as contributing to climate change mitigation and climate change adaptation.

The concept accompanying Sustainable Finance was the "Do Not Significant Harm" criteria: the comprehensive technical assessment performed by the Joint Research Centre[32] and reviewed by two expert groups indicated that "there is no science-based evidence that nuclear energy does more harm to human health or to the environment than other electricity production technologies already included in the EU Taxonomy as activities supporting climate change mitigation" and that the "impacts of nuclear energy are mostly comparable with hydropower and the renewables, with regard to non-radiological effects" .

While nuclear is expected to remain part of the EU's energy mix beyond 2050 following the Commission's forecasts, the issue of sustainability should be put at the core of any design for future SMRs in the EU. This topic should be considered at the earlier stage of the conception of the technology, especially when SMRs would be introduced in the hard-to-decarbonize sectors.

Sustainability, and the objective of achieving a more resource-efficient and circular economy, are crucial for the EU, well reflected in its Treaties, and at the core of the European Green Deal. Sustainability is however a broad and complex concept. According to the 2030 Agenda for Sustainable Development Goals, there are three dimensions to be considered for sustainability: economic, social, and environmental.

To consider the sustainability dimension in the reflections made by the SMR Pre-Partnership, a dedicated task has been created. Its main objective is to analyze to what extent the introduction of LW-SMR and AMR in the EU landscape will contribute to the global sustainability objective of the European Union and define a methodology to measure their benefits.

3.2. Methodology

Firstly, a list of criteria has been established to identify aspects in which the level of sustainability of SMRs could be measured. Different criteria have been discussed based on:

- EU Sustainable Finance;
- UN Sustainable Development Goals;
- Other criteria defined by the expert group to cover the whole dimension of sustainability**.**

It was considered by the task group that the economic aspects (which are not covered by the EU Sustainable Finance) were of big importance when considering economic growth and high-skilled job creation. Another aspect is competitiveness: SMRs should be considered sustainable, meaning affordable to use and operate in the context of their economy. This could be linked with the concept of offering low LCOE to provide affordable and clean energy.

As several criteria covering common objectives, they were merged. Sub-criteria were identified to reflect their relevance for SMRs. The findings described in this report identify benefits from different technologies of SMRs, which highlight their complementarity and the need for deployment of several technologies to grasp the collective added-value SMR and AMR technologies can bring.

Table 4: List of criteria and how their impact should be measured

List of criteria	How criteria are relevant for SMRs
Contribution to the climate change mitigation	High density and reliable low-carbon energy, Easy retrofit of fossil-fuel units, Rapidly deployable, Solution to power small islands and remote places, Complementarity to high intermittent RES fed grid (introduce nuclear source to guarantee a stable source of energy when coupling with intermittent RES), Support production of high-temperature industry (for instance synthetic fuels, chemicals, steel and hydrogen), Target net Zero infrastructure and operations
Contribution to the climate change adaptation	Resilience to severe climate events
Sustainable use and protection of water and marine resources	Low water consumption (when compared to other energy sources)
Clean water and sanitation	Low water warming, Minimum water contamination, Competitive and sustainable water desalination solution (when compared to other energy sources)
Pollution prevention and control: protection of the biodiversity and human beings	Minimum environmental radioactive and hazardous chemical releases, including from normal operation, accidents, waste disposal and dismantling, Minimization of hazardousness of residual waste, Minimization of land-use, and lower materials footprint
Transition to a circular economy	AMR will enable responsible use of fuel primary resources, allow and valorise treatment and recycling of used fuels and radioactive waste, minimum invaluable waste generation
Contribution to socio-economic aspects	Generation of local, sustainable and skilled jobs (including supply chain) generated by SMR deployment & allowing to benefit from a local and skilled supply chain to support facility lifecycle and possible reuse of workforce from the carbon-intensive sectors
Safety, security, non-proliferation	Maximization of Intrinsic risk mitigation, Reduced consequences of accidents allowing Emergency Planning Zone minimization
Harmonization and standardization of nuclear installations in Europe	Transnational social acceptance based on harmonized safety requirements & licensing, Easier participation of local supply chain in nuclear projects in other EU countries
Affordable and clean energy	A value chain allowing a competitive energy price, CAPEX is technically mastered to minimize acquisition, operation and dismantling costs, Robustness of design,

	sustainability of components, low fuel management costs, low waste management costs, intrinsic security and safety features to minimize operation costs, Effective series effect, sharing of risk/opportunity among EU countries
Contribution of the resilient supply chain to achieve innovation and energy independence	Reliable, stable, low-carbon and competitive electricity energy for a strong and growing industry, Intrinsic reliability and level of exposure to external risks (geopolitical, climatic...), Innovative supply chain through modernization of the nuclear and non-nuclear supply chains through innovation and new skills
Insurability aspects	Applicability of the existing nuclear liability regime (Paris Convention) to SMRs If not, the willingness of the (commercial) insurance market to insure this risk/liability

This list has served as a basis for a more qualitative illustrative analysis on how SMR and AMR comply with these criteria, and which technology is well placed to better meet these criteria. It should be noted that the work carried out is a synthesis of the different views of the expert group, spurred by the return of experience of existing nuclear technologies, current literature on SMR and AMR, and announcements made by international and national organizations.

3.3. Main findings from the analysis

3.3.1 Sustainability from an environmental point of view

Nuclear energy is recognized for its low carbon emissions, and some SMR technologies could further reduce the CO_2 emissions through a closed fuel cycle or using recycled materials. They also provide a small footprint thanks to their compact design, even if a large variation exists depending on the concept chosen.

SMRs have the potential to play a significant role to replace fossil energies. A recent DOE report on coal-fired station retrofit by nuclear[33] concluded on the real value of the retrofit option offering a fast track and cost-competitive energy decarbonization solution. The technology could be a differentiator for decarbonization, also given the fact they could be rapidly deployable (SMR mean time for realization typically aims at around 4 years and could be faster for the smaller and most simplified designs).

SMRs could also serve as a good complementary energy source for a highly intermittent RES-fed grid. This is illustrated at least at 3 levels. First, big SMR units can assure the synchronization of the network to deliver high-quality electricity. Second, most of the technologies (LW-SMR, MSR, LFR) are designed with the ability to operate as load followers with fast enough transient capability, others can operate at maximum rate, feeding heat storage when demand allows it and giving back energy when needed. Third, a symbiotic approach could be found for RES and small nuclear generation placed at the same site.

SMRs could provide a solution to decarbonize the high-temperature industry thanks to TRISO fuels used by HTGRs. They could feed the biggest range of industries, including low-temperature metallurgy, thermal hydrogen generation, as well as the chemistry market (MSRs and LFRs are also efficient technologies to address the chemistry market).

In terms of water warming and water consumption, SMRs also present some advantages. For instance, HTGR technology introduce final dry air cooling. High temperature SMRs such as LFR, MSR and HTGR, and mainly HTGR with Direct Gas-turbine cycle, access to higher energy efficiency and by consequence minimize non-used energy needed to be evacuated. Moreover, for SMRs that can be located close to civil infrastructures, they can minimize water consumption and water warming through delivering district and infrastructure heating.

In terms of land use, nuclear energy is by far the most footprint efficient among non-fossil energy sources contemplating the whole value chain. On top of that, SMRs, thanks to their higher nuclear safety features and simpler designs, will call per MW for even less land-use.

3.3.2 Pollution Control

SMRs, like conventional units, implement in their design the concept of multiple barriers between the hazardous source and the environment. The release of radionuclides in the environment and the water are controlled by national authorities and are in reality below the authorized threshold and even below the natural radiation background. Moreover, most of the designs are proposing significant improvements in major accident risks thanks to inherent mitigation features, which reduce the probability of consequences (by at least one order of magnitude). Ultimately HTGRs, LFRs and micro-SMRs using TRISO fuel benefit from the most reliable first barrier in accident situations which has among all the nuclear fuels the highest temperature resistance capacity. The modular approach has the reversible advantage to offer an easier to manage dismantling by differing off-site most of decommissioning waste management activities. LW-SMRs can already claim in their favor access to the HLW management value chain already developed for the conventional units.

3.3.3 Waste management and recycling

Several Advanced SMRs operating with fast neutron spectrum, either with solid or molten fuels, are designed to valorise as energy at the highest rate nuclear materials such as spent fuel, minor actinides, and depleted uranium, while drastically reducing the lifetime of the associated hazardousness. Note that a complete redevelopment of the front and back-end of the fuel cycle will be required for these AMRs to bring such benefits.

When it comes to efficient use of primary resources, fast-breeder AMRs, either with solid or molten fuels coupled with used fuels recycling capabilities, should find their full place within the nuclear ecosystem as the way for valorising depleted uranium stockpiles into energy supply.

In terms of used fuel recycling compatibility, as of today, LW-SMRs' used fuels, similar to conventional units’ fuels, can benefit from access to a proven recycling capability able to add up to 20% more energy generation from fresh fuels while assuring a highly efficient final waste conditioning.

In terms of invaluable waste minimization: fast spectrum reactors, which includes fast spectrum AMRs such as SFRs, LFRs and MSRs, are expected to consume low-grade plutonium and minor actinides refined in advanced used fuel reprocessing capabilities and avoid their disposal in the final repository, reducing drastically the latter sizing constraints while supplying energy.

3.3.4 Safety, security, and non-proliferation

SMR will take typically advantage of all resilience capabilities that have been demonstrated with the current generation of nuclear units, enhanced after the Fukushima accident. Additionally, half-buried core building and inherent safety measures are bringing additional mitigations. Indeed SMRs typically rely on natural phenomena (rather than mechanical components) to passively cool down the reactor and limit radiological risks. The objective is to limit human intervention to reach a safe state even in the most adverse conditions.

In terms of intrinsic risk mitigation and limited Emergency Planning Zone: most SMR designs benefit from passive or inherent features which aim at reducing the risk of a nuclear accident with consequences on the public and environment, so that the EPZ could be limited to the plant footprint. MSRs are inherently stable taking advantage of the favorable behavior of liquid fuel and can switch immediately to a non-reactive state. HTGRs, LFRs, and micro-SMRs using TRISO fuel provide inherently better dissemination and proliferation risks mitigation due to high-performance coating providing robust confinement and dissuasive hard access to the nuclear matter within the fuel.

3.3.5 Sustainability from a social point of view

SMRs have the potential to offer local, sustainable, and skilled jobs on the whole value chain.

During the construction phase, the major consequence of the new SMRs is the surge in manufacturing rate. Getting a local and European benefit from it, as is driven by the rate of supply left by non-European SMR vendors and the ability of local and European suppliers to deliver. It should be one of the major objectives of the partnership. Nonetheless, the EU hosts the comprehensive range of capabilities needed for LW-SMRs and has the competencies to seize the supply market for AMRs.

During the operation phase, SMR plants require operating and support staff and local support contractors. LW-SMRs, which rely on the highest number of activities for operating and require the most frequent outage, are the most demanding in local jobs. In addition, the duration of a construction phase is long enough to prepare the local task force to operate a nuclear plant with the support of very limited neutronic-skilled certified people. The lifetime span of SMRs will guarantee a high level of sustainability for the local jobs.

3.3.6 Sustainability from an economic point of view

Nuclear power plants, as low carbon electricity suppliers, have already demonstrated the high level of reliability they can achieve in many adverse situations, which SMRs/AMRs could equally claim, such as in general they have been assigned the cornerstone role to deliver the electricity baseload. In addition, exposure to fuel cost is limited to 15% and to uranium ore cost around 5%, which led to more predictable and less volatile costs.

Beyond the high ratio of manufacturing, the simplification of the design and the series effect are seen as the main factors bringing the SMR/AMR capital cost per lifetime energy delivered even to most of its efficient competitors. In addition, series deployment should lead to claim minimization of manufacturing and construction risk and in consequence, should allow access to lower financial costs which are prominent in a nuclear new build.

Nuclear power plant experience has demonstrated that nuclear-specific costs are offset by the lower fuel cost per energy delivered and by the concentration of capacity in a single site. Although SMRs will result in lower site capacity, this should remain applicable to site of several hundreds of MW which will remain the rule.

Due to their smaller sizes and improved safety features, SMRs may benefit from better conditions and return rates related to loan and insurance policy, therefore promising lower costs.

3.4. Comparison with other non-nuclear energy sources

A second step of the analysis has consisted in comparing the SMRs and AMRs with other existing and non-nuclear technologies.

Table 5: Comparison between SMRs and other energy sources on the completion of the sustainability criteria

Relevance for SMR	Fossil	Wind	Solar	Biomass
High density and reliable low-carbon energy				
Low carbon	>>	eq	>	>
High density	Eq	>>	>>	eq
Easy retrofit of fossil-fuel units	n/a	Can't	Can't	eq
Rapidly deployable	<	<	<	<
Solution to power small islands and remote places	<	>	>	eq
Complementarity to high intermittent RES fed grid (introduce nuclear source to guarantee stable source of energy when coupling with intermittent RES)	eq	n/a	n/a	eq
Support production of high temperature industry (for instance synthetic fuels, chemicals, steel and hydrogen)	<	>	>	<
Target net Zero infrastructure and operations	>>	eq	>	>
Resilience to severe climate events	eq	>	eq	eq
Low water consumption	eq	<	<	eq
Minimum water contamination	eq	<	<	eq
Competitive and sustainable water desalination solution	eq	>	>	eq
Minimum environmental radioactive and hazardous chemical releases, including from normal operation, accidents, waste disposal and dismantling.	>>	eq	>	>>
Minimisation of hazardousness of residual waste	eq			eq
Minimisation of land-use and lower materials footprint	eq	>>	>>	eq
Allow responsible use of fuel primary resources	<	<	<	>
Allow and valorise treatment and recycling of used fuels and radioactive waste	n/a	n/a	n/a	n/a
Minimum unvaluable waste generation	eq	eq	eq	eq

Generation of local, sustainable and skilled jobs (including supply chain) generated by SMR deployment & allowing to benefit from a local and skilled supply chain to support facility lifecycle and possible reuse of workforce from the carbon-intensive sectors	**>**	**>>**	**>>**	**>**
Maximization of Intrinsic risk mitigation	**eq**	**eq**	**<**	**eq**
Transnational social acceptance based on harmonized safety requirements & licensing	**eq**	**eq**	**eq**	**eq**
CAPEX technically mastered to minimize acquisition, operation and dismantling costs	**eq**	**eq**	**eq**	**eq**
Robustness of design, sustainability of components, low fuel management costs, low waste management costs, intrinsic security and safety features to minimize operation costs	**eq**	**eq**	**eq**	**eq**
Reliable, stable, low-carbon and competitive electricity energy for a strong and growing industry	**>**	**>>**	**>**	**>**

3.5. Partial conclusions and recommendations

The general concept of sustainability and the definition of criteria associated with sustainability has been the results of exchanges in the expert group. This report provides information on how SMRs comply with these objectives as well as a comparison between SMRs and other energy sources on the completion of the sustainable criteria.

It could be indicated that SMRs and AMRs could be considered as sustainable technologies, despite minor differences depending on the technologies.

In terms of next steps, the expert group would recommend the preparation of a more in-depth analysis to pursue the preliminary assessment made in the report, with a solid methodology, to sort and identify new sources, implement quantitative underpinnings.

4. Conclusions

Small Modular Reactors could play a big role in the European energy sector, supporting complementary deployment of low carbon generation of renewables and large nuclear power stations thanks to quick and modular construction. SMRs have the potential to reduce costs, provide power flexibility and deployment flexibility, and present an opportunity for direct replacement of fossil fuel plants. These advantages could make them a cost-effective alternative to renewables and fossil fuels with carbon capture and storage, and could offer an export opportunity for new nuclear energy systems developed in Europe.

This reports highlights the tremendous potential of the SMR Market in Europe through distinct markets: Electricity, Hydrogen production, Industrial heat demand and District Heat demand. Addressing the diversity of all of these markets will require various technologies combining both mature light-water SMR technology for fast deployment and advanced modular reactors capable of reaching higher temperature. These specificities emphasize the need for sectorial approaches so that requirements of large industrials are properly understood and addressed through the right technological vector. It would appear ideal that such approaches would be supported by the EU SMR Partnership.

Following current trends, it is to be expected that SMR deployment will begin around 2030 with a few projects: 2 to 5GW of SMR installed capacity can realistically be expected by 2035 on the EU market (ca. 10 to 20 SMRs). In order to fasten the deployment and obtain a kind of S-curve effect where the rate of deployment increases between 2035 and 2040, the first projects must be successful. This is where the EU SMR Partnership has a key role to play: initiating projects through an enabling framework made of an harmonized licensing scheme, a mobilized and competent supply chain, and R&D initiatives aiming to bring new technologies (including AMRs) into the market. This report estimates to ~20 GW the fleet of SMRs that can be deployed by 2040 if the Partnership endeavours are successful, a four-fold increase to the current projection of SMR project pipelines. Such fleet would represent a contribution to the European economy superior to 7.5 Billion € annually[6].

It is important to note that given the number of reactors to be built (75 – 500 following to the different scenarios considered in this report), series effect is crucial to match the deployment pace (3 to 20 SMR deployed annually). This will only be possible by deploying a limited number of SMR concepts despite what the very large number currently under deployment would indicate. Nevertheless, the market is large and diverse enough for several (~ 5 to 10) technology developers to play a role. It should generally be assumed that about 75% of the SMRs by 2050 will be based on light water technology given the technology maturity and the need for swift deployment of low carbon energy. The rest of it will be based on Advanced technologies (AMRs) to address issues such as the sustainability of the fuel cycle and high-temperature applications.

[6] Conservative assumptions used: each Gigawatt of installed capacity represent a capital investment of ca. 5 billion euros, of which 50% are spent in the European supply chain. This investment is distributed over a period of 5 years. Operational expenditures contributing spent across European suppliers are conservatively estimated to 10 million euros per TWh of electricity generated.

Overall, provided that the deployment success and pace of nuclear energy in the 1970s-80s in Europe can be achieved, a market of ~100GW for Small Modular Reactors by 2050 is possibly available. The net zero 2050 scenario described in the previous sections highlights that this would greatly improve realisticness of achieving net zero in 2050. Such a market could represent more than 20 billion € of annual revenues for EU. These numbers will seem overly ambitious at first glance, but this is mostly because net zero by 2050 is a gigantic challenge, requesting about 9000 TWh of carbon free energy for the sole Europe. One thing is clear: matching deployment pace compatible with such ambitious scenarios will require facilitation in Financing, Licensing, Supply Chain and R&D as is described in the other reports of the EU SMR Pre-Partnership.

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Contributors

Anicet Touré (chair) – Tractebel ENGIE

Varri Konsta (leader Task 1) – Fortum

Emmanuel Girasa (leader Task 2) – ENGIE

Sylvain Esperou du Tremblay (co-leader Task 3) – Orano

Elisabeth Guillaut (co-leader Task 3) – Orano

Guilherme Cardoso – nucleareurope

Joel Carlsson – Vattenfal

Bertrand Charmaison – CEA

Pascal De Langhe – SCK-CEN

Anne Falchi – EDF

Andrei Goicea - nucleareurope

Ivan Horvatovic – SCK-CEN

Sophie McFarlane-Smith – Rolls Royce

Arnaud Paquet – Tractebel ENGIE

David Proult – CEA

Appendix A – Detailed answers to the surveys

Answers to the survey from Nuclear Fora

What is your national roadmap for decarbonization?

Hungary

The National Clean Development Strategy (NCDS) which sets the path for the decarbonization of Hungary's economy by 2050 was adopted by the government on 3 of September 2021. The Strategy is unique in a sense that it is based on an integrated modeling approach to explore the emission trajectories of the sectors as well as the system-wide and cross-sectoral dynamics of the decarbonization process. It is posted on the UNFCCC's official website.

Spain

The National Energy Plan of Spain (PNIEC).

Finland

According to the Government Programme, Finland aims to be climate neutral by 2035 and the world's first fossil-free welfare society. This requires fast emissions reductions in all sectors and stronger carbon sinks. The means to achieve the target include the new climate policy decisions, nearly emissions-free electricity and heat production by the end of the 2030s, and reducing the carbon footprint of building, promoting a circular economy and pursuing a climate-friendly food policy. Sector-specific low-carbon roadmaps have been developed in cooperation with operators in each sector to provide a more accurate picture of the scale, costs and conditions of the measures needed to move to a carbon neutral Finland.

Lithuania

Main direction of Lithuania at present time it is electricity generation from Wind and solar panels, usage of wood for heat and electricity production. Smart grids technology usage. Increase of electrical cars usage by increase of taxes for fossil fuel usage. SMRs are currently not included in the National Energy strategy, but some discussion started.

Sweden

Climate neutrality by 2045. Electrification is a big part of this. Demand is expected to rise from 140 TWh today to +300 TWh 2045. The production of fossil free steel in Sweden will reduce CO-emission in other countries by about 50 Mt CO_2/year and will require 70 TWh of electricity per year for hydrogen electrolysis.

Is nuclear energy part of your decarbonization strategy? Please Explain.

Hungary

Yes nuclear energy is part of the decarbonization strategy. It has two pillars. The extension of operating life time of existing units at Paks NPP, and construction of new units.

Spain

No. The PNIEC foresees the phase out of nuclear generation by 2035.

Finland

Finland is currently preparing a new energy and climate strategy, which includes also nuclear energy and SMRs. The political and public opinion on nuclear is quite supportive, and nuclear will play an important role in Finnish energy mix also in the future.

Lithuania

Until 2004 Lithuania were country with biggest nuclear generation for electricity production within the country. In 2004 and 2009 both Units of Ignalina NPP were shut down as request of joining of Lithuania to EU. Then more than 70 % were imported mostly from Russia. Now import from Russia impossible due to political decisions of Lithuania. But main source of electricity it is import. Nord Pool marked are in place for electricity procurement. Nuclear energy it is not part of Lithuania decarbonization strategy now. Successful implementation of NPP in Poland can be influence to change in strategy will allow to start discussion about usage of Nuclear energy.

Sweden

Yes. The new Government is acting to allow new nuclear possible faster.

Have you already considered using SMRs in your national level energy policy plans?

Hungary

No.

Spain

No.

Finland

Yes.

Lithuania

No.

Sweden

Yes.

At which stage of development are you?

Finland

Early stages, where Finland is mapping the needed regulatory changes to better enable SMRs.

Lithuania

Not started real discussion at national level.

Sweden

Regulations will be developed to allow swift processing of SMR applications, but a lot of work is still required.

Do you think you could envisage SMRs?

Hungary

Yes.

Spain

No.

Lithuania

Yes.

What are the main showstoppers?

Spain

The aforementioned PNIEC

Have you taken concrete steps towards updating your policy to take SMRs into account?

Hungary

No on the policy level.

Finland

Finland is currently reviewing its Nuclear Act. The review will also include changes to better enable SMR projects, e.g. in permitting process.

Lithuania

No.

Sweden

Yes.

What specificities/capabilities do you expect from SMRs to meet the needs of your country (e.g., district heating, high temperature heat, electricity)?

Hungary

There is a potential for district heating and electricity production.

Finland

Especially district heating, but also electricity and hydrogen.

Lithuania

Electricity and district heat production – Benefit of SMR can be only in case if all RAW and SF will be returned to country of origin of SMR (same procedure like with DSRS).

Sweden

All of the above.

What specificities/requirements do you expect from the associated fuel cycle (front-end/back-end)?

Hungary

The fuel cycle has not been evaluated yet.

Lithuania

RAW and SF will be returned to country of origin of SMR. – not so important for Lithuania because we will have DGR but in general it should be main advantage of SMR usage (no RAW will be disposed in country were SMR are used – return to country of origin of SMR).

Sweden

To be determined.

What kind of financial targets would SMRs have to meet for you to see them as viable?

Hungary

Not enough data to give specific answer. In general, affordable energy price seems to be essential.

Lithuania

In general, we expect SMR to be economically competitive with other low-carbon energy sources in the case of electricity and heat (or combined) generation. In the case of renewables, this comparison should also reflect indirect costs of the energy system given by intermittency of renewables. On the other hand, SMRs should benefit from flexible operation in a decentralized energy system. Preliminarily, in terms of LCOE, we consider the values commonly presented by vendors (price of generation of electricity less than 100 EUR per MWh heat price less than 50 EUR per MWh), pretty acceptable.

Sweden

Competitiveness on a deregulated electricity market.

What other benefits could SMRs provide to your needs beyond its decarbonization potential?

Hungary

Security of energy supply.

Lithuania

SMRs could provide security and sustainability of energy supply, research opportunities, new highly qualified and paid jobs, lower emissions, and lower energy costs. Fuel reuse and higher burn-up could be achieved with Generation IV. SMR reactors.

Sweden

Grid stabilization and contribution to electricity transfer.

As EU Member States are positioning themselves as world leaders of the fight against climate change, sustainability has become a cornerstone of every European and national policies and investment projects. Looking at the EU Sustainable Finance criteria and the UN Development Goals, the pre-partnership is identifying a list of aspects that could be addressed by

SMRs. Among this list of sustainability criteria, which ones do you consider as relevant? Is there any other you might otherwise consider?

Hungary

Substantial contribution to climate change mitigation - Climate action

Decent work and economic growth - Fair transition - Job creation - Economic growth

Industry, innovation and infrastructure - Energy independence - Resilience of the supply chain

Finland

Substantial contribution to climate change mitigation - Climate action

Affordable and clean energy

Industry, innovation and infrastructure - Energy independence - Resilience of the supply chain

Sweden

Substantial contribution to climate change mitigation - Climate action

Safety, security, non-proliferation

Affordable and clean energy

Industry, innovation and infrastructure - Energy independence - Resilience of the supply chain

Economic insurability - Financial risk mitigation

Answers to the survey from Member States

What is your national roadmap for decarbonization?

Türkiye

With parallel to Paris Agremment, Türkiye announced zero carbon emission target by 2050. Türkiye's National decarbonization roadmap includes transform into Hydrogen technologies , CCUS technologies, nuclear energy and energy efficiency.

Poland

Poland's national roadmap for decarbonization is outlined in the NECP and the Energy Policy of Poland until 2040 (PEP2040). The latter provides, inter alia, implementation of nuclear energy in 2033, reducing greenhouse gas emissions by 30% by 2030 and increasing energy efficiency by 23% by 2030 compared to the 2007 primary energy consumption projections. According to the document, the share of coal in electricity production will not exceed 56% in 2030 and 28% in 2040. In the light of the Russian aggression on Ukraine, on March 29, the Council of Ministers adopted the Principles for the update of PEP2040 entitled Strengthening energy security and independence.

Czech Republic

Current national roadmap is described by The Climate Protection Policy of the Czech Republic. This document was approved by the Government in 2017 and includes measures for the energy sector, industry, transportation, cross-section measures, waste, research and development, etc. The Climate Protection Policy highlights the importance of nuclear power plants with the agreement to strictly implement the National Action Plan for the Development of the Nuclear Energy in the Czech Republic. SMRs are currently not included in the National Energy and Climate Plan of the Czech Republic (approved by the Government in 2020) and the State energy policy (approved by the Government in 2015). These documents have 5 priorities: a balanced energy mix, savings and efficiency, infrastructure and international cooperation, research, development and innovation, and energy security. State energy policy focuses on renewable, nuclear, and gas sources to provide secure, competitive, and sustainable energy production. The State energy policy should be updated by the end of 2023.

Is nuclear energy part of your decarbonization strategy? Please Explain.

Türkiye

Yes. There is one nuclear power plant at construction phase. Another one is at planning phase. Also there is a research initiative on developing 4th generation SMR technology.

Poland

NECP, PEP 2040, as well as principles for its update envisage introduction of nuclear power as essential for achieving the long-term commitments to reduce greenhouse gas emissions. The role envisaged for nuclear energy has been further underlined by an implementing document - Polish Nuclear Power Programme (PNPP), which provides for the construction and commissioning of 6 large scale nuclear power units with a capacity of 6 to 9 GWe by 2043.

Czech Republic

Nuclear energy has a key role in the decarbonization strategy, as it is included in the State energy policy and in the National Action Plan for the Development of the Nuclear Energy in the Czech Republic. Both documents were approved by the Government in 2015 and focus on the installation of 2 500 MW in new nuclear builds at existing nuclear sites. Both documents should be updated by the end of 2023 with the inclusion of new large nuclear builds and a plan to evaluate the possibilities of SMR deployment as recommended by IEA. Plan to focus on nuclear energy and preparation of SMR roadmap is included in Policy Statement of the Government approved on 6.1.2022 by newly elected Government.

Have you already considered using SMRs in your national level energy policy plans?

<u>Türkiye</u>

Yes.

<u>Poland</u>

No.

<u>Czech Republic</u>

Yes.

At which stage of development are you?

<u>Türkiye</u>

We have just started a feasibility project to create roadmap for developing 4th generation SMR technology.

<u>Czech Republic</u>

The Ministry of Industry and Trade established a working group on the applicability of SMRs in the Czech Republic at the beginning of 2022. The working group includes ministries, the state regulatory body, research institutes, the transmission grid operator, and companies to share knowledge on SMRs and cooperate in the future deployment of SMRs in the Czech Republic. Also, the Czech Ministry of Industry and Trade is in contact with SMR vendors to gain the necessary overview and plans to find new nuclear sites by the end of the year. The Czech Republic is willing to participate and share the knowledge in EU SMR Partnership. Czech companies have been already connected with Nucleareurope to participate in WS4 – Supply chain adaptation.

Do you think you could envisage SMRs?

<u>Poland</u>

Yes.

What are the main showstoppers?

-

Have you taken concrete steps towards updating your policy to take SMRs into account?

<u>Türkiye</u>

Yes. There is a national policy document for 4th generation SMR that starts with aiming to create roadmap for technology development. This project was accepted by Grand National Assembly of Türkiye. According to this document a technology roadmap will be developed by the end of 2022.

Poland

Potential perspective implementation of SMR technology in Poland is reflected in the Principles for the update of PEP 2040. According to said document nuclear energy based primarily on large nuclear reactors of low sensitivity to temporary breakdowns in the supply of fuel and ensuring the supplies of stable and clean energy will be pursued with consistency. The works related to construction of the first Polish NPP and implementation of the Polish Nuclear Power Programme will be accompanied with the parallel efforts aiming at perspective introduction of SMRs.

Czech Republic

The Ministry of Industry and Trade is gathering inputs from the state regulatory body, international associations, companies, research institutes, vendors under the signed NDAs, and other stakeholders to have a sufficient overview regarding the demand and potential use of SMRs in the Czech Republic. The information gathered will be used in the updated State energy policy and the National Action Plan for the Development of the Nuclear Energy in the Czech Republic. A roadmap on SMRs should also be developed next year. Electricity and heat demand for the chemical and steel industry are being evaluated and will have a significant impact on future energy consumption as well as SMR potential use. The Czech Republic has approved Coll On Supported Energy Sources (known as Lex Dukovany), which can be applied also in the case of SMRs, and the Ministry of Industry and Trade is undertaking necessary steps for faster SMR deployment. For example, the Line act should speed up the construction of transport, water, energy, and electronic communications including nuclear power plants and SMRs.

What specificities/capabilities do you expect from SMRs to meet the needs of your country (e.g., district heating, high temperature heat, electricity)?

Türkiye

The expected capabilites are, electricity, residential and industrial heating, hydrogen production.

Poland

In general we envisage for SMRs potential deployment for electricity and heat co-generation for industrial purposes and for district heating systems According to the said Principles, using SMRs to produce the process heat may offer an alternative to the conventional units for the industry and heating sector. In the electrical power sector, such distributed units – not replacing the systemic large nuclear blocks –may act as an additional component of diversification of the power generation structure and strengthen the energy security at the local level.

Czech Republic

The Czech Republic is focusing on replacing coal-fired power plants, which have been used for electricity and heat production. The SMRs should create an opportunity to replace those units and use cogeneration to produce low-carbon electricity and heat for central heat systems. The possibility of hydrogen production is supported and being evaluated. High-temperature heat could benefit industry requirements, but generation IV. reactors are not in the state to be deployed in the Czech Republic in the near future.

What specificities/requirements do you expect from the associated fuel cycle (front-end/back-end)?

Czech Republic

To be assessed.

What kind of financial targets would SMRs have to meet for you to see them as viable?

Czech Republic

In general, we expect SMR to be economically competitive with other low-carbon energy sources in the case of electricity and heat (or combined) generation. In the case of renewables, this comparison should also reflect indirect costs of the energy system given by intermittency of renewables. On the other hand, SMRs should benefit from flexible operation in a decentralized energy system. Preliminarily, in terms of LCOE, we consider the values commonly presented by vendors (mostly ranging from 30 to 100 EUR per MWh), pretty acceptable.

What other benefits could SMRs provide to your needs beyond its decarbonization potential?

Türkiye

SMR can be a solution for heat and electricity supply to the district regions. It may also supply necessary heat for the industry with zero carbon emission.

Czech Republic

SMRs could provide security and sustainability of energy supply, research opportunities, new highly qualified and paid jobs, lower emissions, and lower energy costs. Fuel reuse and higher burn-up could be achieved with Generation IV. SMR reactors.

As EU Member States are positioning themselves as world leaders of the fight against climate change, sustainability has become a cornerstone of every European and national policies and investment projects. Looking at the EU Sustainable Finance criteria and the UN Development Goals, the pre-partnership is identifying a list of aspects that could be addressed by SMRs. Among this list of sustainability criteria, which ones do you consider as relevant? Is there any other you might otherwise consider?

Türkiye

Substantial contribution to climate change mitigation - Climate action

Climate change adaptation

Transition to a circular economy

Industry, innovation and infrastructure - Energy independence - Resilience of the supply chain

Poland

Substantial contribution to climate change mitigation - Climate action

Pollution prevention and control - Good health and well-being - Protection and restoration of biodiversity and ecosystems - Life below water - Life on land

Decent work and economic growth - Fair transition - Job creation - Economic growth

Harmonization and standardization of nuclear installations in Europe

Affordable and clean energy

Industry, innovation and infrastructure - Energy independence - Resilience of the supply chain

Appendix B – survey to be addressed to the industry

In the frame of the European SMR Partnership, this survey aims to understand the needs and requests of potential users of SMRs in the future. This survey is addressed to companies and/or associations of companies active in the electricity and industrial sectors.

Note: for the questions, YOU may either mean YOUR COMPANY or the MEMBERS REPRESENTED BY YOUR ASSOCIATION.

The survey is structured as follows:

- Your profile
- Your interests for SMRs
- Your possible options
- Your sustainability criteria

1.Please identify your activity area (single choice).

Electricity

Heat production

Chemistry

Petrochemistry

Metals

Glass

Ceramics

Cement

Pulp and paper

Other

2.Could you be more precise about the purpose of your company / organization? (free answer)

3.Are you (mainly) an energy producer or consumer? (single choice)

Producer

Consumer

Both

4.What are the territories/countries of interest for your activities? (free answer)

5.Have you already considered using SMRs for your activities? (single choice)

Yes

No

6. (If no to Q5) Do you think you could envisage SMRs? (single choice)

Yes

No

7. (If no to Q6) What are the main showstoppers? (free answer)

8. (if yes to Q5) At which stage of development are you? (free answer)

9.What are your **mid-term needs** (<2040)? Which use? (multiple choice)

Electricity

Heat

Other

10.What are your mid-term needs (<2040)? Please provide an order of magnitude of unitary & cumulative power envisaged (MWe, MWth). (free answer)

11.What are your mid-term needs (<2040)? Do you need flexible power output? If yes, please precise (a typical load profile/power consumption curve on a daily/weekly/monthly/yearly basis, if possible). (free answer)

12.What are your mid-term needs (<2040)? When it's key for you, please provide specific requirements (heat temperature/pressure, island mode/connected, black-start capability, backup system, …). (free answer)

13.What are your mid-term needs (<2040)? What specificities/requirements do you expect from the associated fuel cycle (front-end/back-end)? (free answer)

14.What are your mid-term needs (<2040)? Do you have a preferred SMR technology? (single choice)

Yes

No

15.(If yes to Q14) What are your mid-term needs (<2040)? Which technology? (free answer)

16.What are your **long-term needs** (>2040)? Which use? (multiple choice)

Electricity

Heat

Other

17.What are your long-term needs (>2040)? Please provide an order of magnitude of unitary & cumulative power envisaged (MWe, MWth). (free answer)

18.What are your long-term needs (>2040)? Do you need flexible power output? If yes, please precise (a typical load profile/power consumption curve on a daily/weekly/monthly/yearly basis, if possible). (free answer)

19.What are your long-term needs (>2040)? When it's key for you, please provide specific requirements (heat temperature/pressure, island mode/connected, black-start capability, backup system, …). (free answer)

20.What are your long-term needs (>2040)? What specificities/requirements do you expect from the associated fuel cycle (front-end/back-end)? (free answer)

21.What are your long-term needs (>2040)? Do you have a preferred SMR technology? (single choice)

Yes

No

22.(If yes to Q21) What are your long-term needs (>2040)? Which technology? (free answer)

23.Would the SMR need to be located close to your site(s)? (single choice)

Yes

No

24.Could the SMR be shared between industries close to your sites? (single choice)

Yes

No

25.What would be your preferred option regarding the operation of the SMR? (single choice)

Power purchase agreement (PPA) only

Ownership but minimum liability (SMR operation by a third party)

Fully licensed nuclear operator

Other

26.What kind of financial targets would SMRs have to meet for you to see them as viable? (free answer)

27.SMRs have to address different aspects of sustainability: the supply of low-carbon, affordable, rapidly and easily deployable, reliable, and resilient source of energy, which limits resources consumption, fosters fuel circular economy deployment and minimizes environmental impacts, providing lasting local and skilled jobs throughout the value chain, while guaranteeing the highest level of safety and security of the supply. In general, how far is your understanding of SMR as a sustainable source of energy? (free answer)

28.SMRs have to address different aspects of sustainability: the supply of low-carbon, affordable, rapidly and easily deployable, reliable, and resilient source of energy, which limits resources consumption, fosters fuel circular economy deployment and minimizes environmental impacts, providing lasting local and skilled jobs throughout the value chain, while guaranteeing the highest level of safety and security of the supply. Which sustainable aspects would you consider as a real added value for your SMR project/for your energy transition? (free answer)

29.Do you have any additional comment(s)? (free answer)