ORIENT- NM

Organisation of the European Research Community on Nuclear Materials

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

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

Start date of project	01/10/2020
Duration	30 months
Reporting period	1 - 01/10/2020 – 30/03/2022

Work Package 1 – Dialogue with Member States and European Commission

Deliverable 1.3:

Summary of national programmes on nuclear materials

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Date of issue	30/11/2021	
Date of final approval	13/12/2021	
Dissemination Level		
PU	Public	X
CO	Confidential, only for partners of the ORIENT-NM Action and the EC	

Version	Date	Description

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List of abbreviations

AC	Associated Countries
ALFRED	Advanced LFR European Demonstrator
ALLEGRO	(no precise meaning, GFR European Demonstrator)
AMR	Advanced Modular Reactor
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
BWR	Boiling Water Reactor
CANDU	CANadian Deuterium Uranium (reactor)
EC	European Commission
EPR	European Pressurized Reactor
EU	European Union
GFR	Gas-cooled Fast Reactor (GenIV)
GenII/III/III+	Second/Third/Third+ Generation (currently operating)
GenIV	Fourth Generation (next generation)
GIF	Generation IV International Forum
HTGR	High Temperature Gas-cooled Reactor
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
INDC	Intended National Determined Contributions
ITER	International Thermonuclear fusion Experimental Reactor (The Way)
JHR	Jules Horowitz Reactor
LFR	Lead-cooled Fast Reactor (GenIV)
LWR	Light Water Reactors
LTO	Long-Term Operation
MS	Member States
MSR	Molten Salt Reactor (GenIV)
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
NDE	Non-Destructive Examination
NE	Nuclear Energy
NECP	National Energy & Climate Plan
NM	Nuclear Materials
NPP	Nuclear Power Plant
PMa	Programme Manager
POw	Programme Owner
PWR	Pressurised Water Reactor
R&D	Reserch and Development
RPV	Reactor Pressure Vessel
SCC	Stress Corrosion Cracking
SCWR	SuperCritical Water-cooled Reactor (GenIV)
SFR	Sodium-cooled Fast Reactor (GenIV)
SMR	Small and medium-size Modular Reactor
VHTR	Very High Temperature Reactor (GenIV)
VVER	Water-Water Energetic Reactor (PWR of Soviet design)
WNA	World Nuclear Association

Summary

By consulting the National Energy and Climate Plans (NECPs), as well as the country profiles of IAEA and WNA, complemented by information from websites of other international organisations, or press and scientific articles, it was possible to track how nuclear energy generation will continue and evolve in Europe (MS and AC) until 2040 and beyond, trough GenIII/III+ new builds (and uprates) and lifetime extension (LTO).

For as much as can be projected at the time of writing (November 2021), the number of current generation nuclear power units will overall decrease in the “West” of the EU (with the exception of France), but will increase in the “East” and in the ACs.

It was also possible to identify the interests of each MS and AC for next generation reactors, i.e. small and medium size modular reactors (SMRs) and GenIV systems, which overlap with each other through the concept of advanced SMR, or AMR. Several countries, including some that do not currently operate any nuclear reactor, expressed interest in deploying SMRs or in considering GenIV systems. In addition, several countries, including those that are phasing out or did phase out, as well as some currently without nuclear power, have to face decommissioning of nuclear installations. Thus only very few countries have no nuclear energy related interests at all.

It is concluded that by 2040 the installed nuclear power in Europe may be very close to what it is in 2021, and that game-changers such as SMRs and fourth generation systems may lead to a nuclear resurgence around and beyond 2040, especially if curbing the greenhouse gas emissions proved even more difficult than currently expected.

In this framework, the European nuclear materials science community is therefore called to provide the tools, knowledge and skills to enable each European country to maintain the wished and needed nuclear capacity, as well as to introduce such capacity, and/or, depending on specific national policies and interests, to develop advanced nuclear systems.

Thus the research activities of a European partnership dedicated to nuclear materials should support:

- Safe and affordable LTO of current generation reactors;
- Increasingly safe design, licensing and construction of Gen III+ new builds;
- Deployment of light water SMRs within the next decade;
- Reduction of time and costs for the design, licensing and construction of competitive next generation (GenIV) nuclear reactors, including advanced SMRs, within the time horizon of 2040.

How this can be done is the topic of the vision paper and of the strategic research agenda of ORIENT-NM.

1. Introduction

One of the most important tasks in ORIENT-NM is to describe the overall picture of the nuclear materials research interests of the EU member states (MS) and associated countries (AC), as this is one of the starting points to build a research agenda that should be consistent with those interests.

With this purpose in mind, a questionnaire has been prepared and distributed to as many Programme Managers (PMa), located in the various MS and AC, as possible. The distribution list included mainly members of the ORIENT-NM consortium and, when not, the contacts were anyway obtained through members of the consortium. It was however difficult to identify correct PMa contacts for all MS/AC: this limited from the start the possibility of being fully exhaustive. The overall methodology concerning questionnaires is described in the deliverable D1.2 “Questionnaire to request input from MS and relevant national committees”.

Input was received from PMa of 15 MS/AC, namely: Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Italy, the Netherlands, Poland, Romania, Slovenia, Slovakia, Spain and Switzerland. In the case of two countries, two separate questionnaires were filled in by different contacts, but were not necessarily fully consistent with each other, either in terms of interpretation of the questions, or in terms of answers; three of the questionnaires were incomplete. The results of the analysis of the questionnaires are collected in the **Annex**.

The questionnaires, although some of them provided interesting and useful hints, did not provide sufficient information to be able to draw general conclusions. In a way, the main outcome has been that hardly any MS/AC has any *specific* nuclear materials (NM) research programme or strategy, although most have a nuclear energy development programme. From these programmes, nuclear materials research interests can be, however, deduced. Thus the objective of this task turned into identifying the nuclear energy interests of the various MS/AC.

In order to identify the national nuclear development programmes, other sources than the questionnaires had to be consulted, namely:

[1] National Energy & Climate Plans (NECP) [1] that each EU MS produced in 2019 and revised in 2020, after receiving comments from the EC;
1) IAEA and WNA country profiles [2,3];
2) GIF website [4];
3) Other sources, mainly press articles available from the web (referenced throughout the document).

In what follows, the outcomes of the analysis of the above documents are graphically presented through maps of Europe, in which colour-codes are used to convey the information.

Clearly, the information reflects what could be deduced from the sources at the <u>time of consultation of the documents</u>, i.e., in <u>November 2021</u>.

2. Summary of the situation of nuclear energy in Europe at the time of writing

Figure 1 shows that, in 2020, nuclear energy emerged as being the single largest source of electricity in the European Union (EU). Importantly, it was also the single largest source of electricity *free of greenhouse gas (GHG) emissions*.

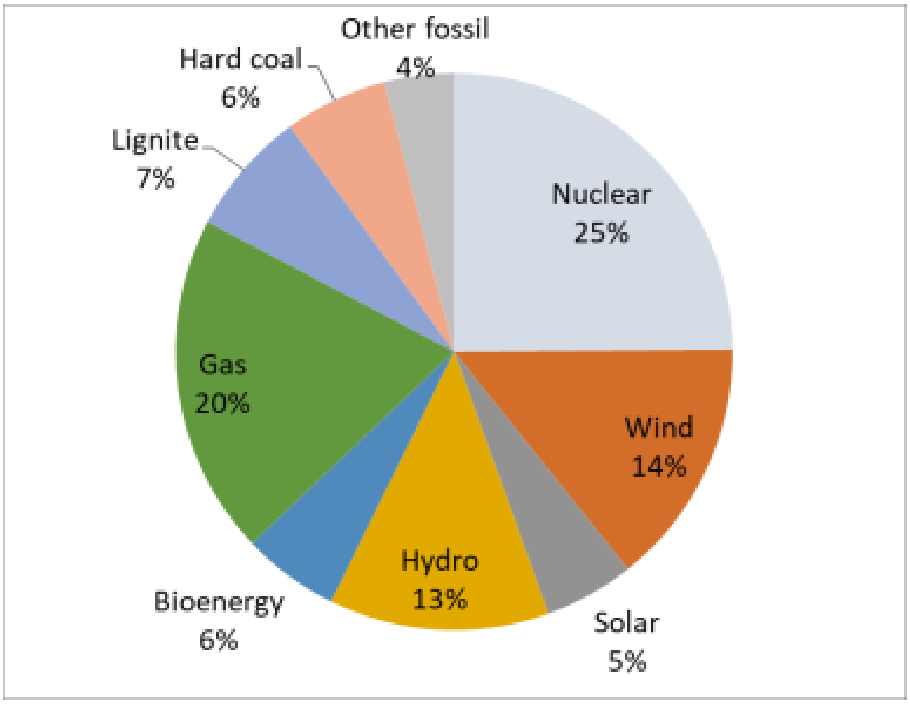


Figure 1. *Electricity generation in the EU in 2020, by source. Data from Eurostat (2020) [5].*

Figure 2, in turn, illustrates how nuclear power plants (NPPs) are distributed in Europe (as of February 2020): countries with plants that are operating or under construction are highlighted differently from those that have none. The figure distinguishes between EU and non-EU countries, however it has to be remembered that Armenia, Switzerland, Turkey, UK, and Ukraine, though not part of the EU, are EU-*associated* countries and they all have nuclear power plants, either operating or (TK) under construction. The evolution from this situation, based on what could be foreseen in 2021, using the sources that are mentioned above, will be shown and discussed in the next section.

Table 1 provides more details per EU country about nuclear energy generation as of February 2021, as well as number and power of operating reactors, reactors under constructions, and planned or proposed reactors. Summing reactors that are being constructed, are planned or are proposed, 26 new units should be built from now to the 2040s in the EU, corresponding to about 16 GWe of installed power. Currently, 106 reactors are operating, corresponding to about 104 GWe installed. Some of these reactors will be shut down over the analysed timeframe, especially in countries that have decided to phase out, with more or less extended calendars of closure. For example, while Germany, Belgium and Spain have established precise and relatively early dates for the progressive closure of their NPPs, Sweden and Switzerland have not put any date and are also in fact extending the lifetime of the plants, so that they are likely to be still having operating reactors beyond 2040. Most other reactors will keep operating, as most of them have undergone or are undergoing lifetime extension beyond their design lifetme, as well as power uprates. Because of the different calendars adopted by each country to implement their nuclear plans, however, the situation will evolve in a non-linear way over the years, as is shown in the next section.

Finally, **Figure 3** shows that 5 types of reactors are currently operated in EU MS and AC: namely both types of light water-cooled reactors (LWR), i.e., pressurized and boiling water reactors (P/BWR), water-water energy reactors (VVER, Soviet design version of the PWR), heavy water-cooled reactors (CANDU) and the remaining advanced graphite-moderated gas-cooled reactors (AGR) in the UK. This information is important in connection with the determination of the interest for specific nuclear materials and relevant issues that may be specific for some countries.

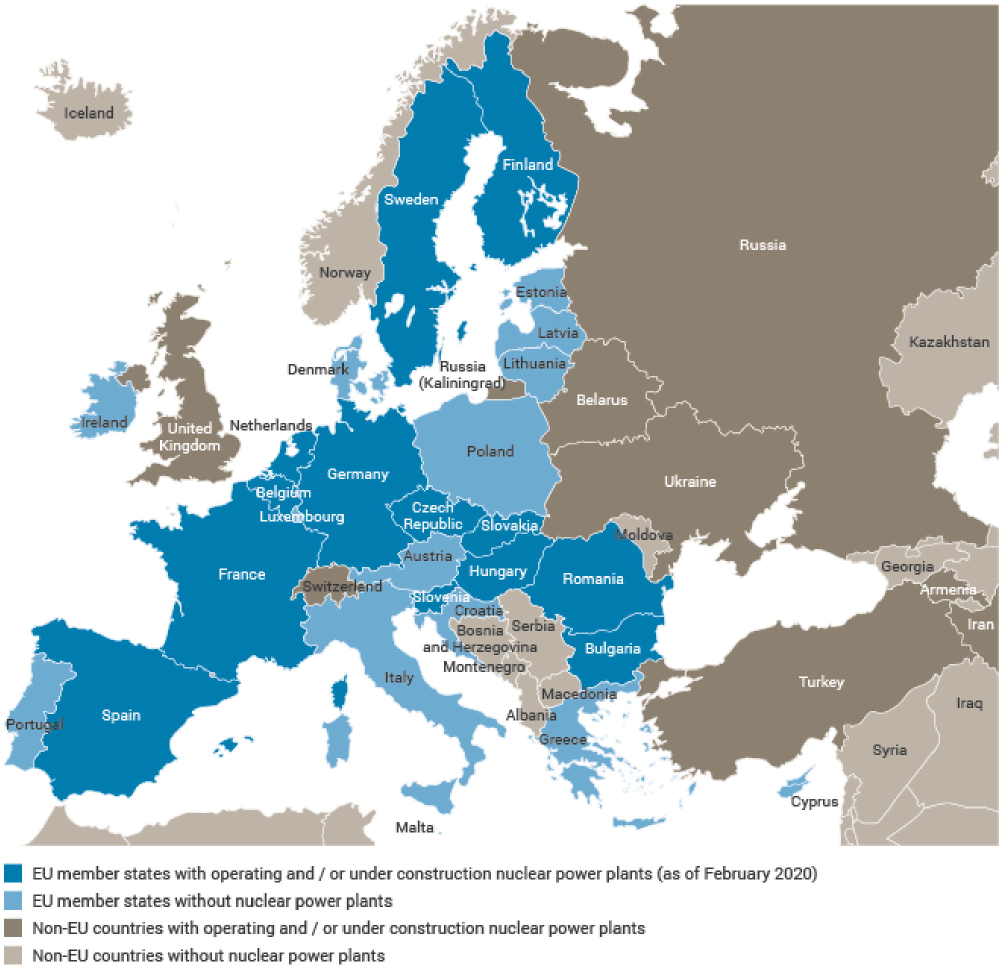


Figure 2. *Distribution of nuclear power plants in Europe, operating and under construction. Source WNA [6].*

Table 1. *Details on the number of NPPs (operating, under construction, planned and proposed) and corresponding power as of February 2021. Source WNA [6].*

COUNTRY	NUCLEAR ELECTRICITY GENERATION (2019)		REACTORS OPERABLE		REACTORS UNDER CONSTRUCTION		REACTORS PLANNED		REACTORS PROPOSED	
	TWh	% e	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross
Belgium	41.4	47.6	7	5930	0	0	0	0	0	0
Bulgaria	15.9	37.5	2	2006	0	0	1	1000	1	1000
Czech Republic	28.6	35.2	6	3932	0	0	1	1200	3	3600
Finland	22.9	34.7	4	2794	1	1720	1	1250	0	0
France	382.4	70.6	56	61,370	1	1650	0	0	0	0
Germany	71.9	12.4	6	8113	0	0	0	0	0	0
Hungary	15.4	49.2	4	1902	0	0	2	2400	0	0
Lithuania	0	0	0	0	0	0	0	0	2	2700
Netherlands	3.7	3.2	1	482	0	0	0	0	0	0
Poland	0	0	0	0	0	0	0	0	6	6000
Romania	10.4	18.5	2	1300	0	0	2	1440	1	720
Slovakia	14.2	53.9	4	1814	2	942	0	0	1	1200
Slovenia	5.5	37.0	1	688	0	0	0	0	1	1000
Spain	55.9	21.4	7	7121	0	0	0	0	0	0
Sweden	64.4	34.0	6	6859	0	0	0	0	0	0
EU	**732.6**	**26%**	**106**	**104,311**	**4**	**4312**	**7**	**7290**	**15**	**16,220**

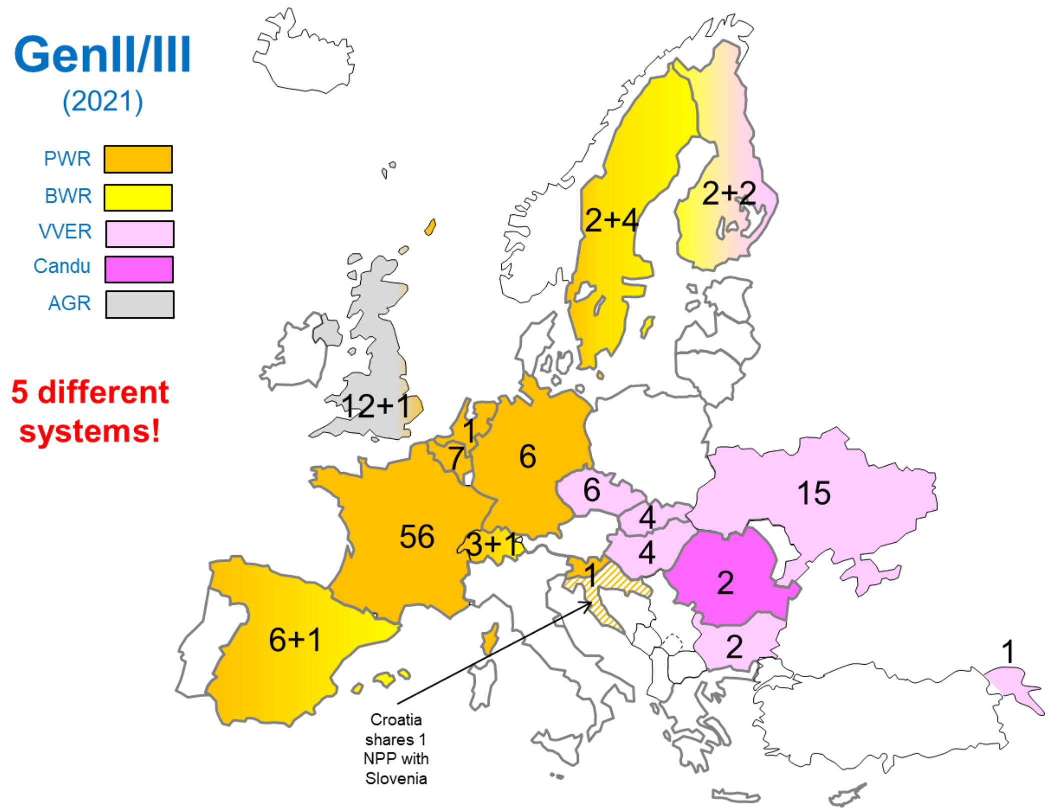


Figure 3. *Types of reactors deployed in the EU MS and AC.*

3. Nuclear energy evolution in Europe from 2021 to 2040 (and beyond)

Figures Figure 4 toFigure 9 summarize the evolution in the number of operating nuclear reactor units in the EU MS & AC from 2021 to 2040, based on applied or existing plans of long-term operation (LTO), new builds, and phase out calendars, for as much as can be projected from 2021. This projection is based on declared intentions in countries that are planning and proposing the construction of new reactors or are planning LTO, or are phasing out, as described in the documents listed in the Introduction[1]. It also accounts for the expressed intention of considering nuclear options in countries that currently do not have any nuclear installation, and thus in some cases need to become equipped with suitable legislation. This is the case of Poland, that has declared the intention of building NPPs, and already hosts nuclear installations, but also of Estonia [7] and perhaps Ireland [8] as well, which never built any nuclear installation, but expressed interest for small and medium-sized modular reactors (SMR).

Numbers in red on the countries denote a change with respect to the previous snapshot, the arrow indicating whether increasing or decreasing. When there are uncertainties about the number of reactors that will have been actually built or shut-down at some point in time, the total listed on the right-hand-side of the figure indicates minimum and maximum values that are compatible with the envisaged plans. From 2030 on, SMRs are expected to appear on the market and be deployed. However, they are not counted in the total on the right-hand-side of **Figures Figure 4 to Figure 9**, because of the difficulty of foreseeing their number and power. Thus, theirs possible deployment is simply indicated as "SMR" on the corresponding country or countries.

It is important to emphasise that most EU MS and AC with NPPs have already extended, or are planning to extend, the lifetime of their units up to 50-60 years, which corresponds to increasing by 10-20-25 years, the design lifetime, depending on the type of reactor. This happened even in countries that are planning to phase out, such as Spain and Belgium. But there are cases in the world where 80 year are targeted, as well, e.g. in the US [9]. The Netherlands may be considering this option for its only reactor [10], while in Switzerland there is no predefined shutdown date for the remaining NPPs, and the requirement for extension is that a 10 years license renewal is requested, which is granted if the NPP is demonstrated to be safe, so 80 years might be reached there, too. The situation with LTO in Europe is summarized in **Figure 10**.

[1] The details based on which the figures have been built can be found in a working document stored at http://www.eera-jpnm.eu/orient-nm/filesharer/documents/Useful%20Reference%20Documents (Working Document for Deliverable D1.3).

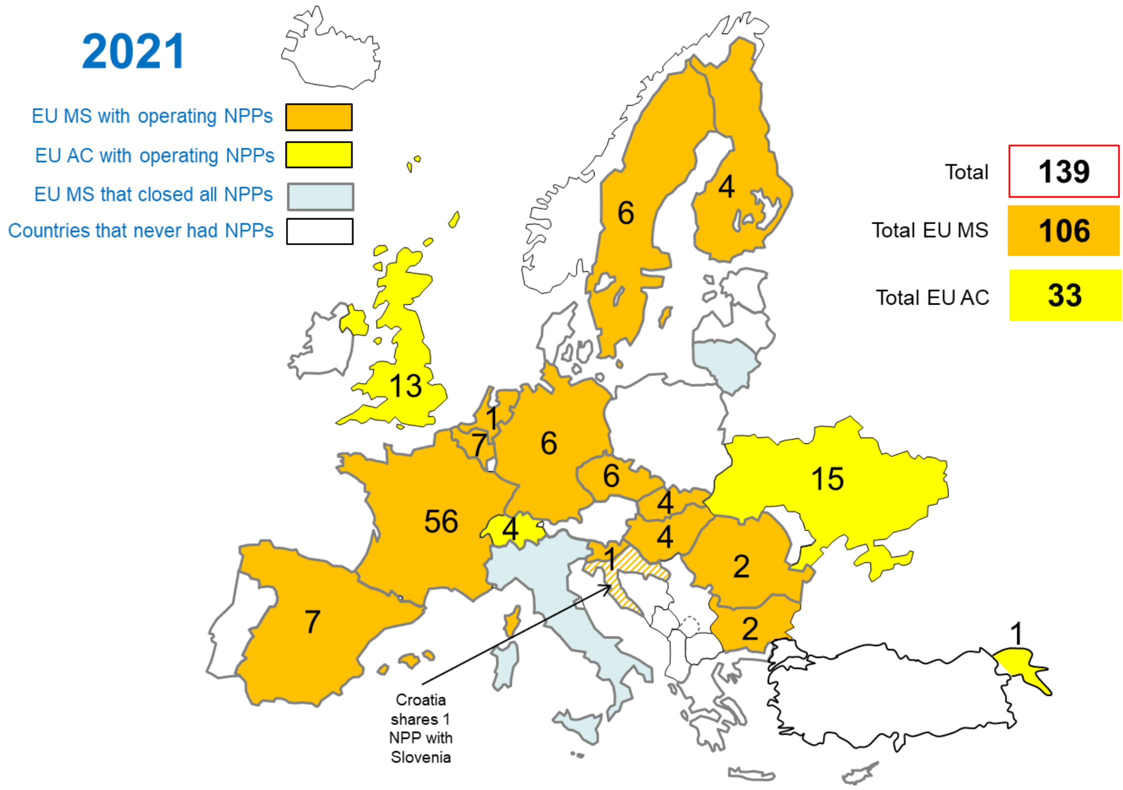


Figure 4. *Number of operating nuclear reactor units in EU MS & AC in 2021.*

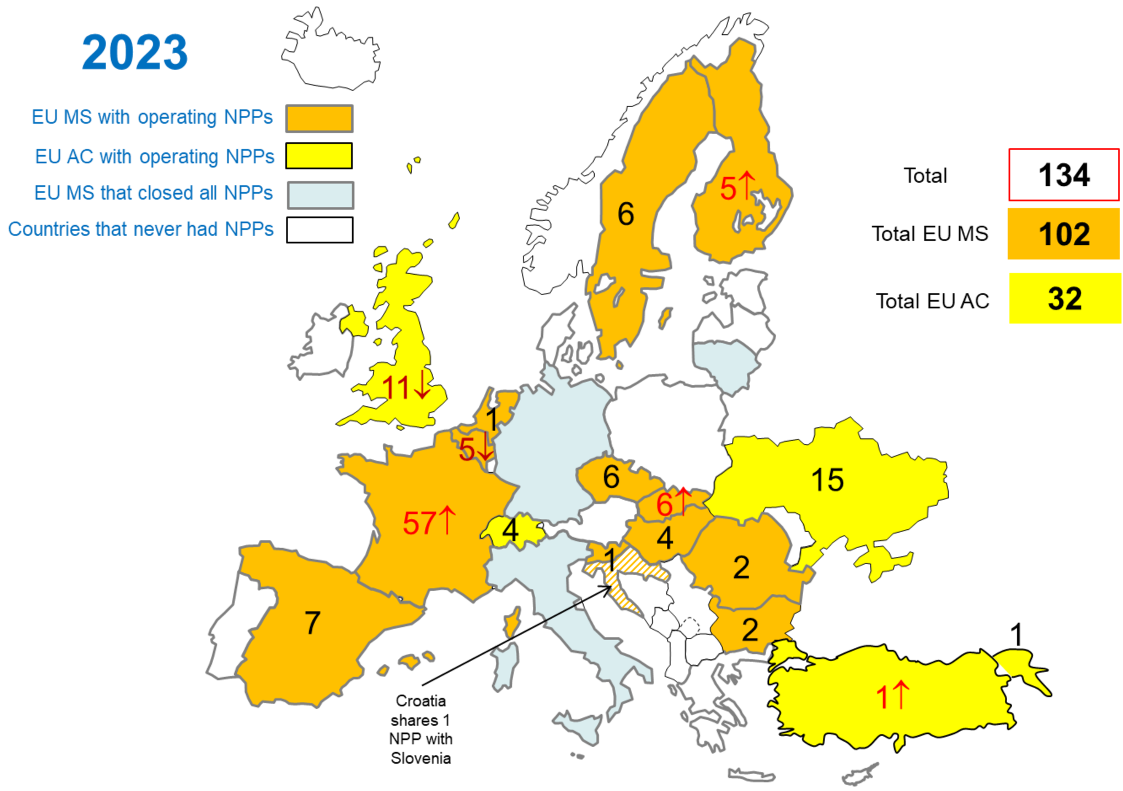


Figure 5. *Expected number of operating nuclear reactor units in EU MS & AC in 2023 (projection from 2021).*

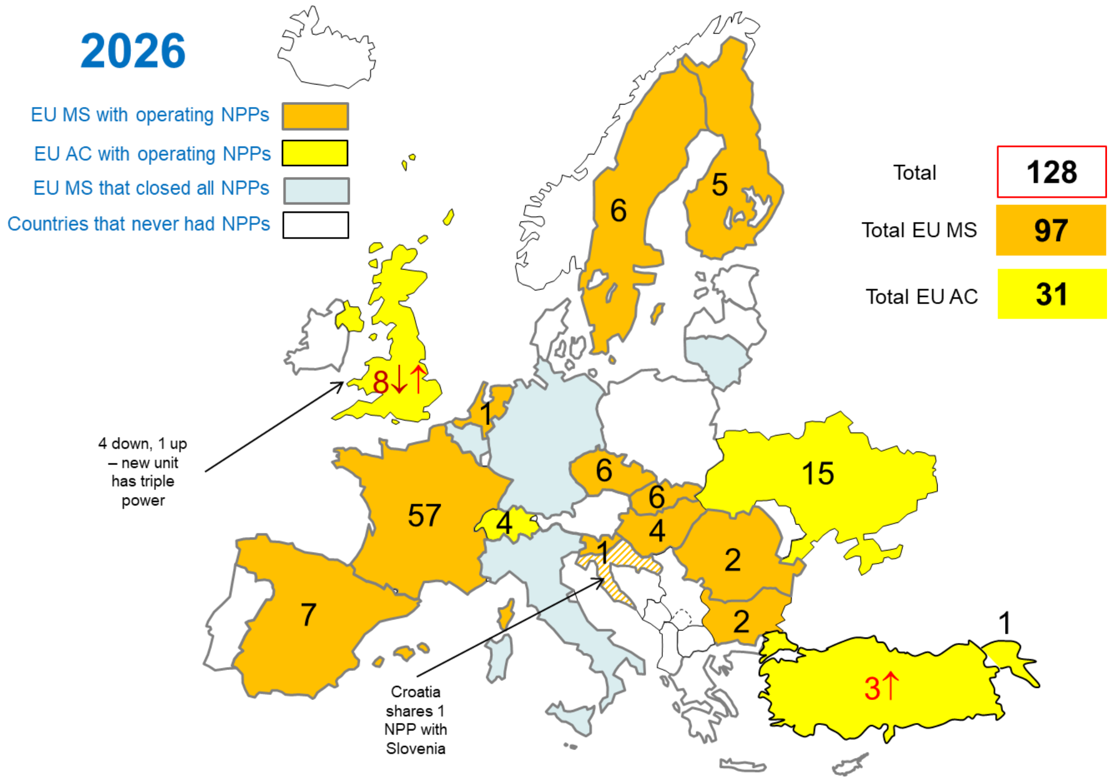


Figure 6. *Expected number of operating nuclear reactor units in EU MS & AC in 2026 (projection from 2021).*

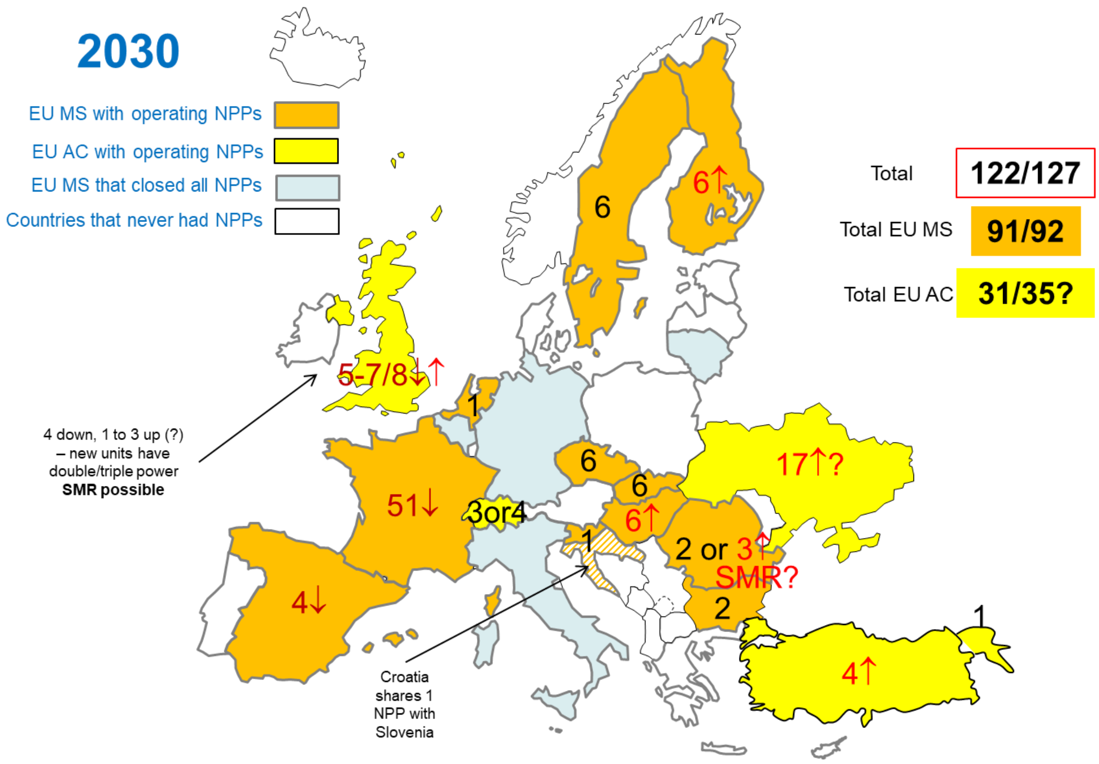


Figure 7. *Expected number of operating nuclear reactor units in EU MS & AC in 2030 (projection from 2021).*

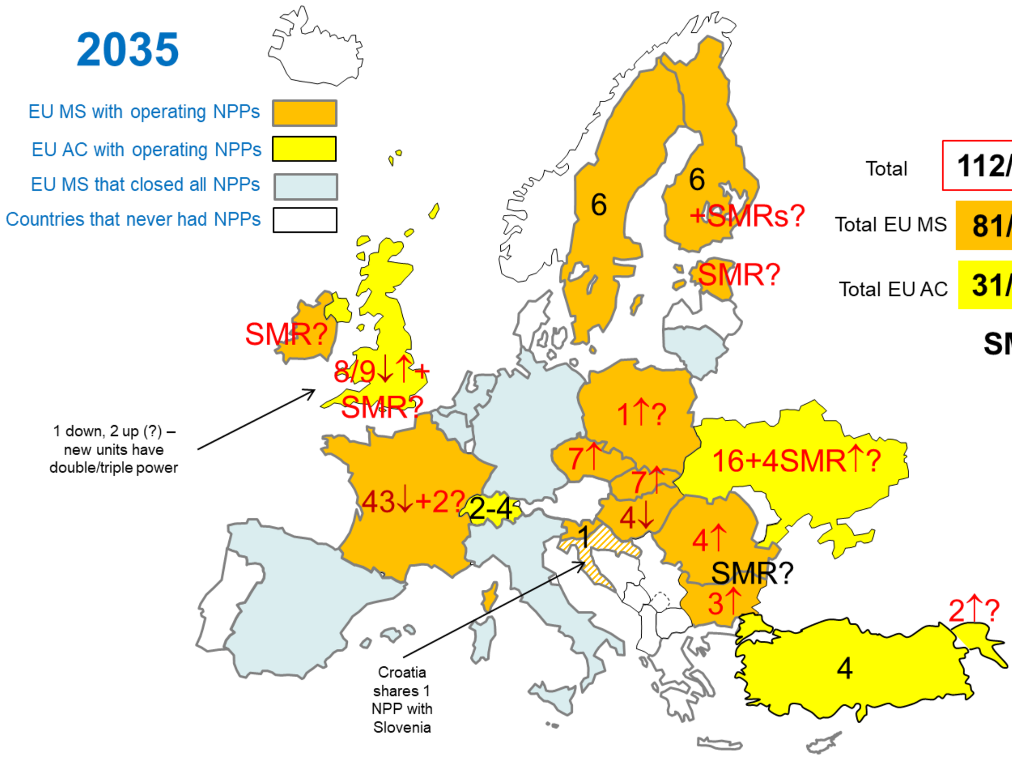


Figure 8. *Expected number of operating nuclear reactor units in EU MS & AC in 2035 (projection from 2021).*

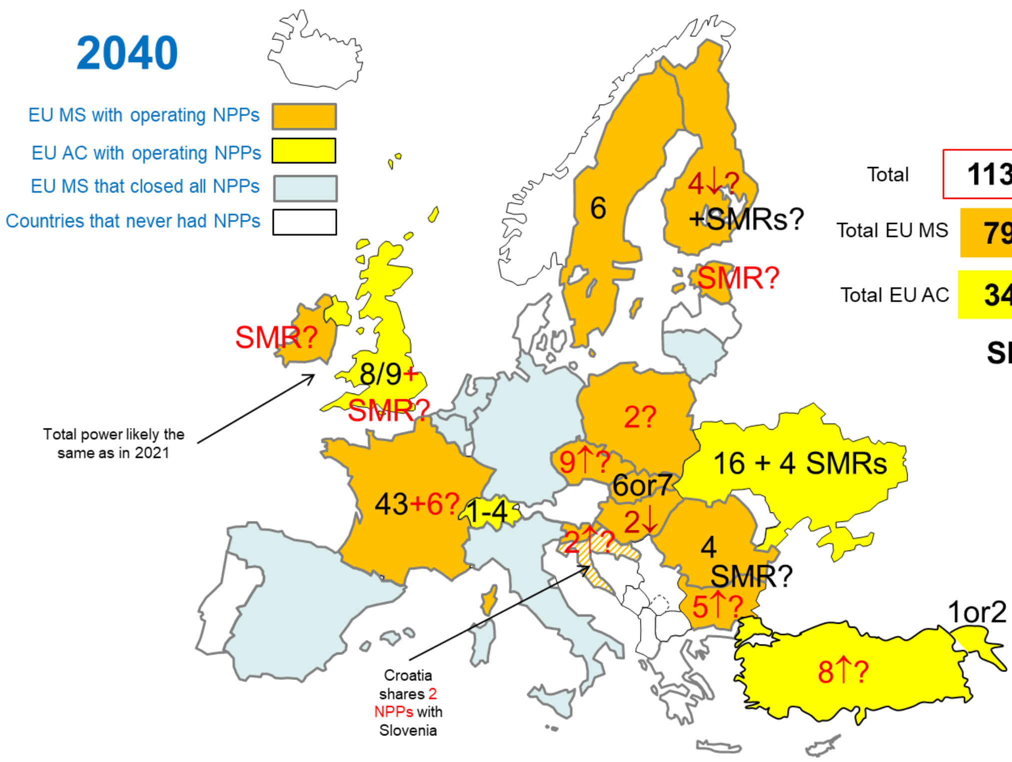


Figure 9. *Expected number of operating nuclear reactor units in EU MS & AC in 2040 (projection from 2021).*

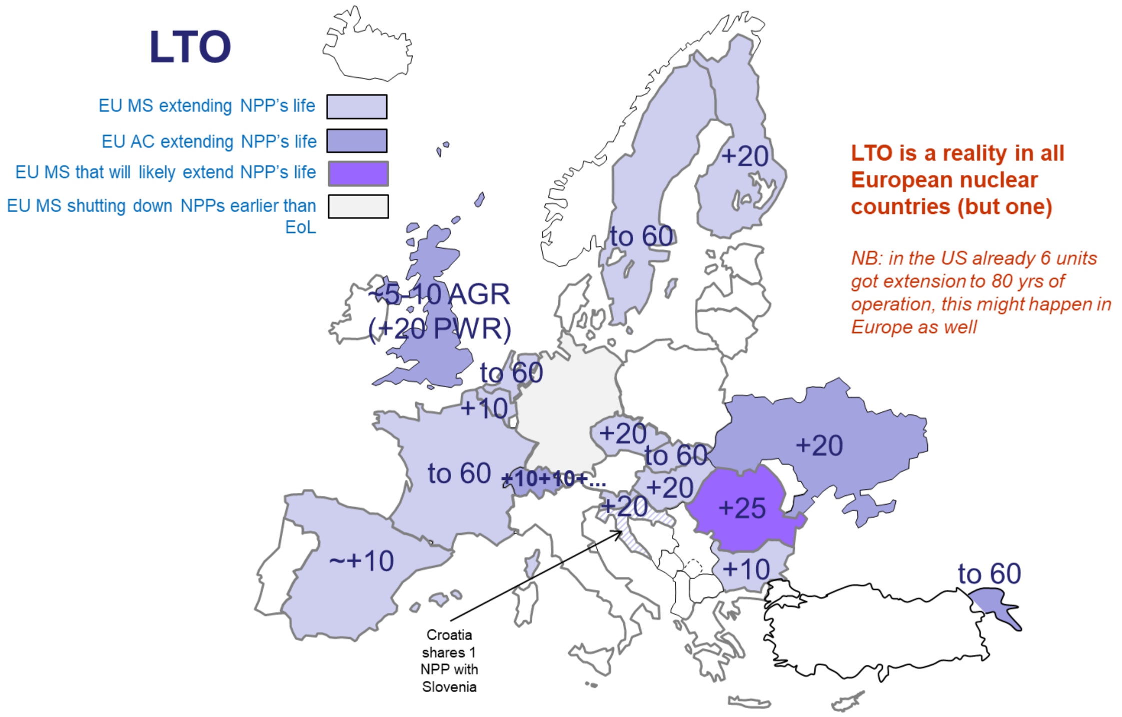


Figure 10. *Summary of lifetime extension beyond design of NPPs in EU MS and AC (either specifying by how many years, +, or up to how many years).*

The inspection of **Figures Figure 4 to Figure 9** reveals that the overall number of reactors is decreasing in Europe, especially in the EU, as a consequence of the phasing out decision of some large nuclear countries that are progressively shutting down all their NPPs without replacement. However, several smaller MS, especially in Eastern Europe, have plans (according to their NECPs) to keep using NPPs and build new ones, with Poland being added to the group of countries with operating NPPs. On the other hand, ACs such as the UK and Turkey have ambitious plans of nuclear expansion, Turkey soon entering the group of countries with operating NPPs and targeting a total of 8 units. If the number of NPPs does not grow more than what the figures show, it is because most MS opting for this source of energy in the EU are small. Therefore, the construction of 1-2 new units, combined with LTO, is often enough to cover their needs. But the number of countries following this option is far from negligible. Thus, the number of NPPs in Europe by 2040 might be between 20 and 10 % less than now. But the trend when building new units (that are not SMRs) is to install higher power ones, shifting from 400-600 MWe/unit to 1000-1200 MWe/unit. Moreover, if SMRs are deployed, there will probably be a fair number of them. Overall, therefore, even with 20% less large reactor units than in 2021, the installed nuclear power in 2040 in Europe is likely to be on the same order as, or even higher than, in 2021. Of course, however, the largest part of the installed power in 2040 will still come from lifetime extension of old NPPs. Without plans to build new ones, such as for example in Sweden and Switzerland that will likely exceed 2040 with LTO, the decrease in number of reactors and therefore installed power after this year may be drastic, as is shown in **Figure 11**; even more if the SMR technology does not take off for whichever reason. This is the *low-nuclear* scenario.

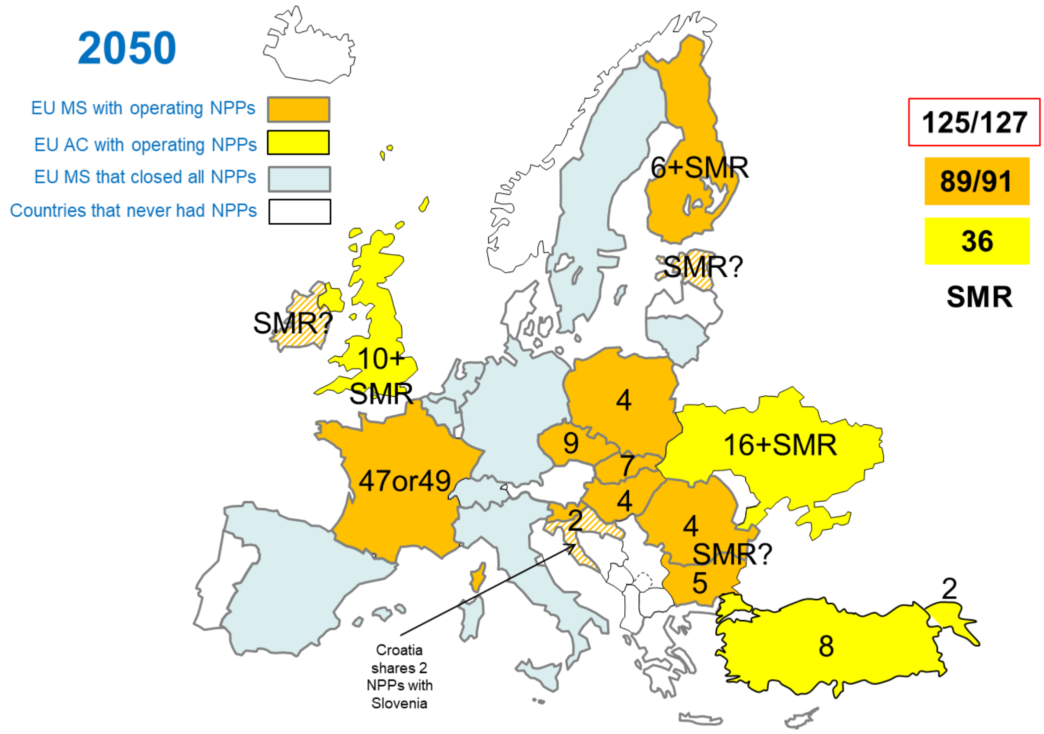


Figure 11. *Low-nuclear scenario in terms of remaining nuclear reactor units in operation in EU MS & AC in 2050 (projection from 2021).*

However, other nuclear scenarios are possible, as well. Policy changes may occur, if bending the GHG emission curve turned out to be more difficult than envisaged, despite the serious commitment of the EU and other countries around the world to take ambitious steps in this direction, by significantly increasing the share of renewables. A perception of this difficulty is given for example by **Figure 12**, in which the GHG emission paths over time towards the 1.5 and 2ºC of average temperature increase by 2050 are compared with the paths with and without intended nationally determined contributions (INDCs), i.e. with or without the declared efforts to reduce GHG emissions by the countries that committed themselves to do so. The figure is by now oldish (2016, COP 22 [11]) and for sure the current commitments, if actually realized, enable a closer path to the target to be followed. However, it is clear that the gap between actual GHG emission decrease and target decrease is large and the change of slope that should be achieved in a reduced number of years to comply with the objectives is daunting. In this context, any NPP that is shut down represents an increase in GHG emissions, unless it is fully and rapidly replaced by a significant deployment of renewables; which, however, calls for an even larger one to enable the reduction in the use of fossil fuels, too. In fact, in most cases NPPs are replaced by gas-fuelled power plants, at least temporarily, because NPPs provide stable and abundant supply of energy, which is not simple to replace with renewables in a short amount of time. The nuclear contribution to making the energy transition possible is thus undeniable, as is explicitly recognized even in the NECP of a country like Spain, which has decided to phase out, but to do so gradually, in order to comply with the energy transition requirements. Thus, in a context of effort to bend the GHG emission curve, there is an obvious advantage in postponing the closure of NPPs and there is also an advantage in giving continuity to nuclear with new builds. For this reason, the Netherlands might pragmatically consider a new build in addition to more extended LTO of the single NPP the country currently hosts [10], while the decision of Sweden not to build any more NPPs is not yet 100% firm, as can be deduced from its NECP. Moreover, nuclear reactors can be used to produce also heat and hydrogen (so-called *pink, or purple, hydrogen* [12,13]), which is depicted as the best option as non-fossil fuel of the future, particularly for transport [14]: these could be strong additional market reasons to keep exploiting NPPs and even build new ones [13].

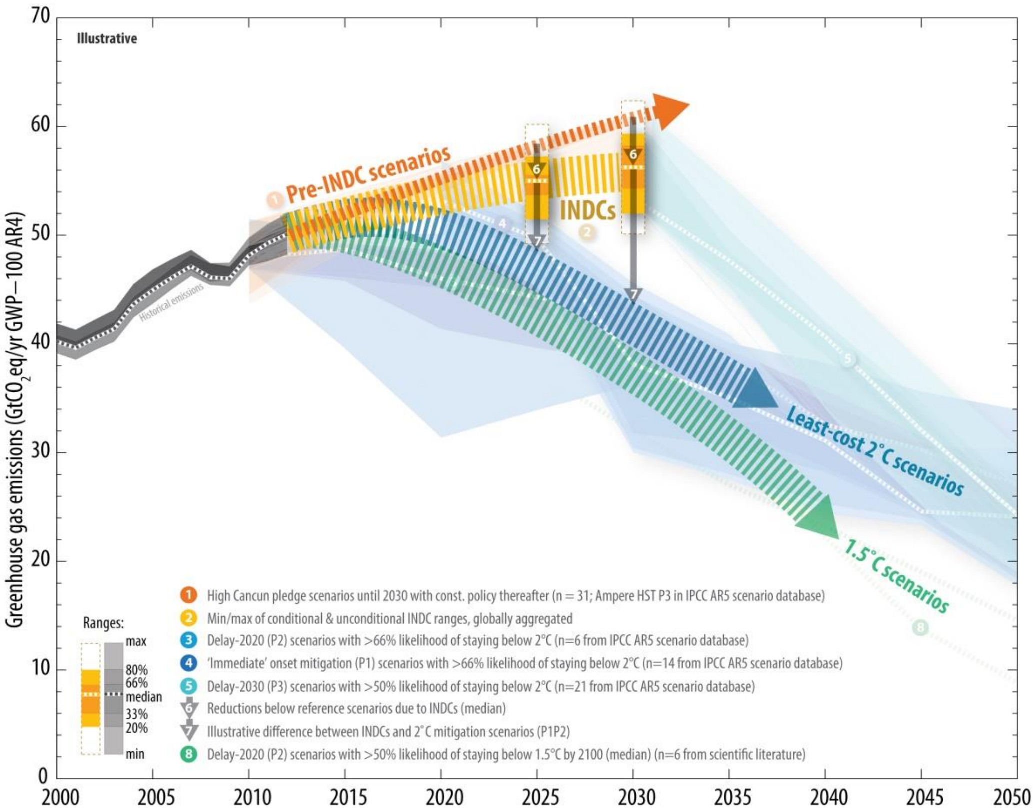


Figure 12. *Comparison of the effect of the intended nationally determined contributions (INDC) on GHG emissions, and the paths that should be followed to realize the 2ºC or the 1.5ºC scenarios by 2050 [11].*

The SMR technology is still under development, so it is difficult to make reliable predictions about its market. However, it is clearly raising significant interest (see next section), and is expected to be a game-changer, which, as mentioned, might make nuclear energy attractive also for countries (particularly small ones) that have never had any NPP [7,8]. Finally, next generation reactors, particularly those belonging to the fourth generation (GenIV) portfolio [4], which promise, on the one hand, drastic waste reductions in a circular economy, and, on the other, higher efficiency, including high temperature heat production for industrial use, do raise interest in several countries, including some that do not have NPPs, because of their higher flexibility and sustainability, as is detailed in the next section.

All these reasons lead to suppose that the installed nuclear power in 2040 may be larger than currently envisaged and by 2050 nuclear energy might be steeply resurging as an attractive technology to counteract climate change, through SMRs and next generation technologies.

4. Next generation reactors in Europe

SMRs as a concept are perceived as game changers by the nuclear industry, which are expected to make nuclear energy attractive for a wider market, because of increased flexibility, shorter construction times and high safety standards. The closest-in-time SMRs are light water-cooled ones (LW-SMR), e.g. Nuward in France [15]. In parallel, fourth generation systems are slowly under development through the design and construction of prototypes and demonstrators, and bear the promise of drastically reducing nuclear waste, by adopting a circular economy, increasing efficiency, guaranteeing high safety standards, and expanding the use of nuclear energy to heat production in co-generation systems, for example enabling hydrogen production via highly efficient thermochemical processes, rather than by electrolysis [16]. High temperature reactors and most GenIV reactor concepts are, in addition, compatible with the concept of SMR, so-called advanced SMRs (A-SMR, or AMR), thereby overall offering a much higher flexibility and better economy for the use of nuclear power. Accordingly, several EU MS/AC have an interest for these systems.

Two MS, namely France and Estonia, explicitly mentioned LW-SMRs in their NECP, although in the former case most likely for export, while in the latter as an attractive solution for a small country that does not have access to significant renewables because of geophysical reasons. As mentioned, Ireland is also considering this option. Many MS have either research activities connected with SMR or A-SMR development, or host startups that are betting on either SMR or A-SMR solutions, and many have GenIV-connected projects, which often overlap with A-SMR plans. This is summarized in **FiguresFigure 13, Figure 14 and Figure 15**.

Fortum in Finland [17] and the state-owned utilities of Romania and Bulgaria [18], as well as the governements of the UK [19] and Ukraine [20] as ACs, have defined plans to deploy SMRs, as soon as the technology is on the market. Romania talks about commissioning in 2027-2028 [18]. All are correspondingly working on a suitable regulatory framework.

Companies working on the development of lead-cooled fast SMRs exist in Sweden [21] and Luxembourg [22], while in the UK facilities for the development of this technology are being built [23] and Westinghouse has its own lead-cooled modular fast reactor design under development [24]. Italy and Romania share interests in the construction of the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED), through the Falcon Consortium, with the involvement of Ansaldo Energy and ENEA [25]: the plans for ALFRED’s construction are mentioned in the Romanian NECP and next generation SMRs are currently at least a topic of discussion at political level in Italy

[26]. Finally, remaining in the liquid lead-cooled type of technology, Belgium is developing Myrrha (Multi-purpose hYbrid Research Reactor for High-tech Applications, [27]), a lead-bismuth eutectic-cooled accelerator-driven system (ADS [28]), which, although not meant to produce energy, does adopt GenIV type technology.

On another front, Denmark hosts two startups that are designing thorium-based small and modular molten-salt reactors (MSR), one of which floating [29,30,31]. In addition, the Netherlands [32] and the Czech Republic [33] host respective consortia dedicated to the design of small MSRs; France as well has interests in MSR development [34]. At the same time, even though the construction of a sodium-cooled fast reactor (SFR) prototype of fourth generation, ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration, [35]) has been currently shelved, France keeps working at this technology with a long term programme [36].

Poland, in addition to planning the construction of current generation NPPs, is also considering the deployment of high temperature gas-reactors (HTGR) [37], of already established technology [38], for industrial heat production in cogeneration systems, with the interest also of Slovakia, Czech Republic and Hungary, as well as France, Finland and the UK [39]. The four Višegrad countries are also working on the design of the gas-cooled fast reactor (GFR) demonstrator, ALLEGRO [40,41], within the V4G4 consortium based in Slovakia [42], with the technical support of France [41]. Slovakia and Czech Republic mention this commitment explicitly in their NECP. The Czech Republic has also ongoing research activities in connection with materials for the SuperCritical Water-cooled Reactor (SCWR), together with several other, among which Finland and Spain [43].

Concerning ACs, the UK and Switzerland belong to the GIF (together with the EU through Euratom and JRC, and with France): their interests there range from the SFR to the (very) high temperature reactor (VHTR) [44]. Consistently, the UK government has recently chosen the HTGR for its Advanced Modular Reactor Programme [45].

5. Decommissioning and other nuclear connections in Europe

Irrespective of the intention of continuing or not to exploit nuclear energy, about 2/3 of the EU MS, including for example Italy and Lithuania that do not currently have operating NPPs, and, among the ACs, Switzerland, the UK and Ukraine, are all going to have to face the issue of decommissioning NPPs. In addition, Norway is currently dismantling the experimental reactor at Halden, that operated from 1958 to 2018 [46]. This is summarized in **Figure 16**. Moreover, out of 9 EU MS that have never had any NPP, and have likely no intention of building any (except perhaps Ireland and Estonia), Portugal and Denmark did host experimental reactors (the Danish ones have been dismantled, the Portuguese one is permanently shut down), while in Greece the testing reactor at the Demokritos research centre is still in operation. Austria dismantled a NPP before its completion. Outside the EU, Serbia might be considering the possibility of building a NPP in the future [47]. This is summarized in **Figure 17**. Thus, the number of European countries that really do not have, and likely will not have, any connection with nuclear installations, is actually very small (Albania, Bosnia-Herzegovina, Cyprus, Kosovo, Iceland, Latvia, Luxembourg, Malta, Moldova, Montenegro and North Macedonia).

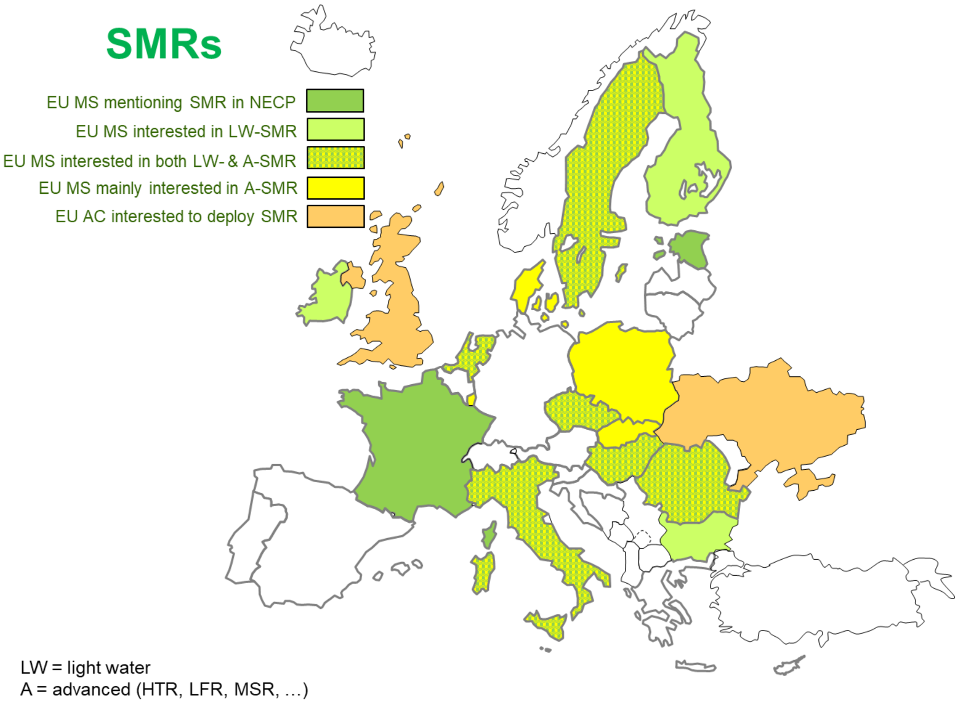


Figure 13. *Interest for SMRs and A-SMR, either because of expressed intention of deploying them, or because of the presence of startups that are betting on specific SMR or A-SMR technologies.*

6. Conclusions

By consulting the National Energy and Climate Plans (NECPs), as well as the country profiles of IAEA and WNA, complemented by information that is available through websites of other international organisations, or published in press or scientific articles, it was possible to get a fairly **clear idea of how nuclear energy generation will continue and evolve in Europe (MS and AC) until 2040 and beyond**, trough GenIII/III+ new builds (and uprates) and lifetime extension (LTO). For as much as can be projected **at the time of writing (November 2021)**, the number of current generation nuclear power units will overall decrease in the "West" of the EU (with the exception of France), but will increase in the "East" and in the ACs.

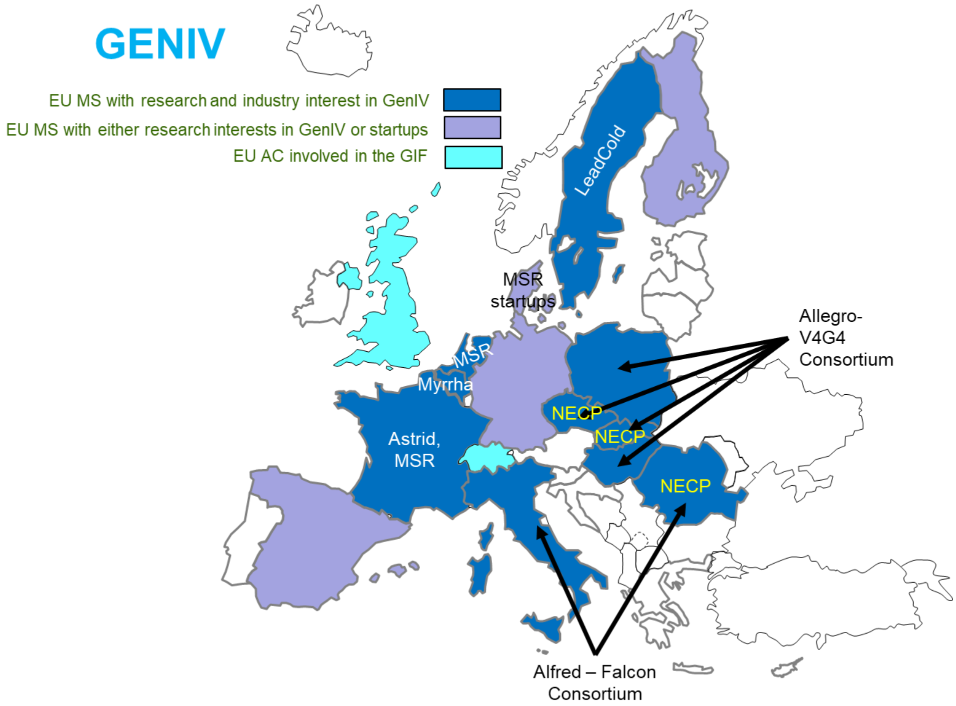


Figure 14. *Interest for GenIV reactors, either because of expressed intention of developing them, e.g. on NECPs, or because of the involvement in consortia or presence of startups, or participation in GIF.*

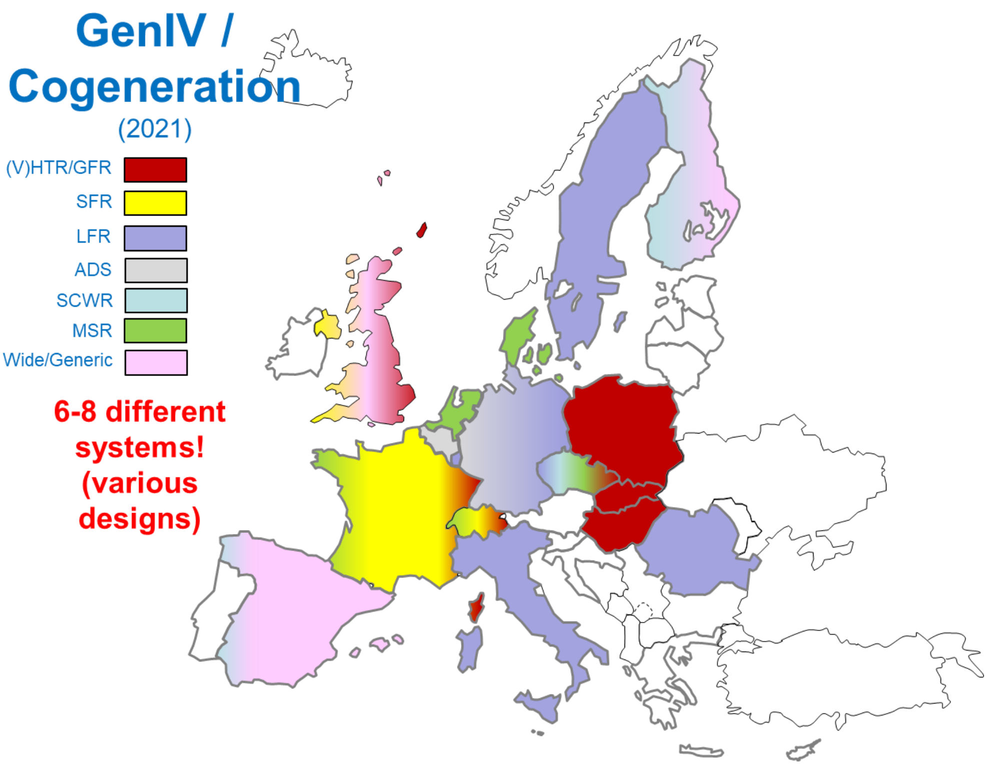


Figure 15. *GenIV systems of interest in the various EU MS and AC.*

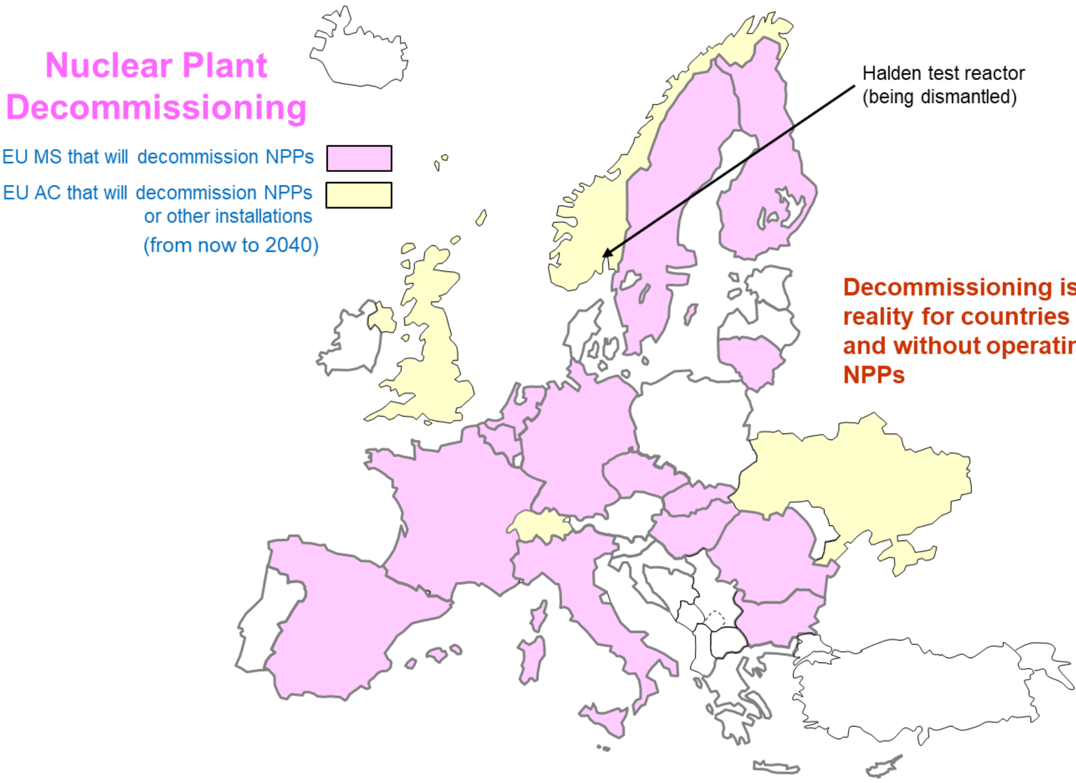


Figure 16. *European countries where nuclear plants will be decommissioned.*

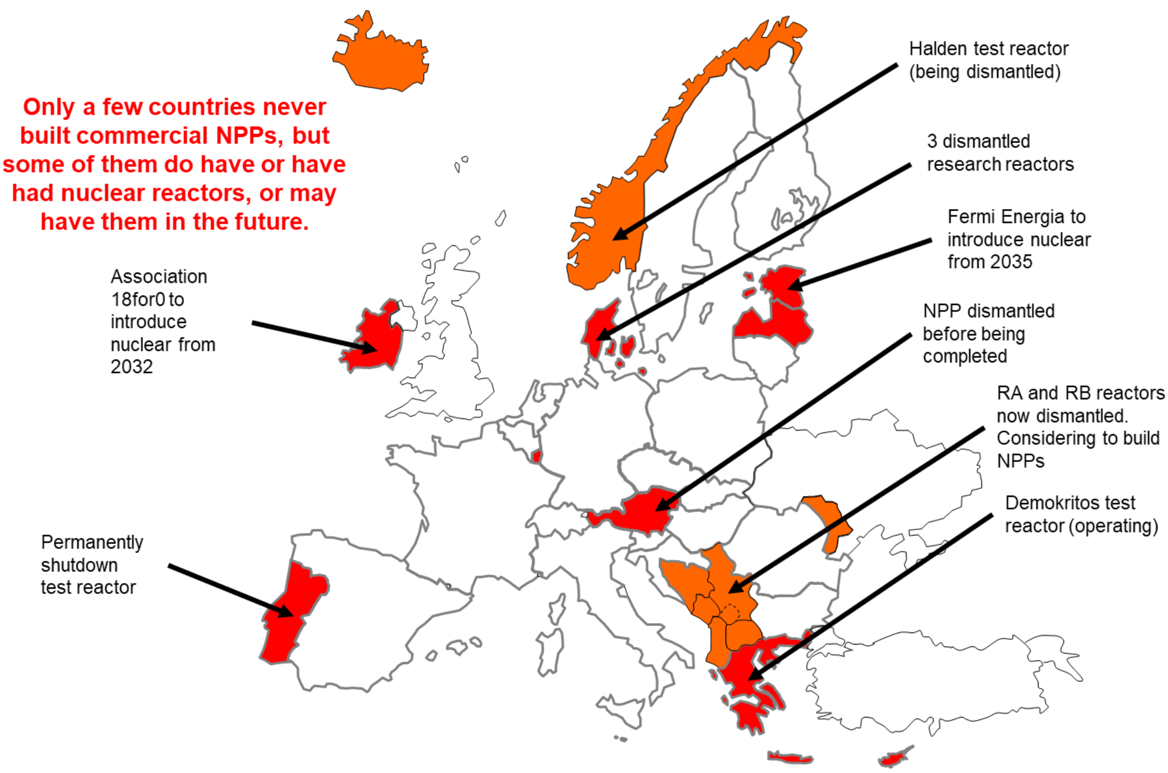


Figure 17. *Connection with nuclear in non-nuclear (no NPPs) European countries.*

It was also possible to identify the interests of each MS and AC for next generation reactors, meaning by this small and medium size modular reactors (SMRs) and GenIV systems, which overlap with each other through the concept of advanced SMR, or AMR. It appears that **several countries, including some that do not currently operate any nuclear reactor, expressed interest in deploying SMRs or in considering GenIV systems**. In addition, several countries, including those that are phasing out or did phase out, as well as some currently without nuclear power generation, have to face decommissioning of nuclear installations. Thus only very few countries have no nuclear energy related interests at all.

It is concluded that **by 2040 the installed nuclear power in Europe may be very close to what it is in 2021**, and that **game-changers such as SMRs and fourth generation systems may lead to a nuclear resurgence around and beyond 2040**, especially if curbing the greenhouse gas emissions proved even more difficult than currently expected.

In this framework, the European nuclear materials science community is therefore called to provide the tools, knowledge and skills to enable each European country to maintain the wished and needed nuclear capacity, as well as to introduce such capacity, and/or, depending on specific national policies and interests, to develop advanced nuclear systems[2].

Thus the research activities of a European partnership dedicated to nuclear materials should support:

- **Safe and affordable LTO of current generation reactors;**
- **Increasingly safe design, licensing and construction of Gen III+ new builds;**
- **Deployment of light water SMRs within the next decade;**
- **Reduction of time and costs for the design, licensing and construction of competitive next generation (GenIV) nuclear reactors, including advanced SMRs, within the time horizon of 2040.**

How this can be done is the topic of the vision paper and of the strategic research agenda of ORIENT-NM.

[2] For decommissioning other initiatives exist already, i.e. SHARE (StakeHolder-based Analysis of REsearch for Decommissioning, https://cordis.europa.eu/project/id/847626).

Annex – Analysis of the questionnaires answered by PMa of various MS/AC[3]

1) National policies concerning nuclear energy (in bold those that answered the questionnaire, in parenthesis ACs; concerning countries that did not answer, the information was deduced from the analysis of nuclear profiles and news)

Phase out: **BE DE ES (CH)**
Expand: **BG CZ FI HU RO SI** (AM[4] UK UA TK)
Continue at the same level or with mild expansion: **FR**, HR**, NL, SE**
Planned adoption of nuclear energy: **PL**
The possibility of adopting nuclear energy is discussed, whichever the outcome: EE IE **IT**
No nuclear and no intention to consider it: AT, CY, DK, GR, LT, LU, LV, MT, PT

2) Types of reactors for which R&D interest has been expressed *(in italics deductions from other sources than the questionnaire)*:

Type of reactor	Large reactors	SMR (if applicable)
PWR	BE BG CZ FI FR DE HU NL SI SK ES SE (CH)	BG CZ FI FR HU RO SI
BWR	SE ES NL DE FI (CH)	
VVER	BG, CZ, DE, FI, HU, SI, SK **6**	BG, CZ, SI
CANDU	RO	
Magnox	*UK*	
GenIII/III+	CZ FI*(EPR)* FR(EPR) DE HU NL SI SK	CZ NL SI
SFR	FR DE NL	NL SI
LFR	FR DE RO SE *IT*	BE NL RO SI SE *IT*
GFR	*CZ* FR HU *PL* SK	*CZ* HU *PL* SI SK
(V)HTR	FR SK PL	BG NL SK *PL*
SCWR	FR CZ DE RO SE	CZ SI
MSR	CZ FR DE HU	CZ HU NL
Other (specify)	FR(JHR), FI(EPR, AES2006, VVER1200) CH(zero power CROCUS, SINQ)	
Fusion reactors	BE, CZ, FR(ITER), DE, HU, SI, SK, SE *BG FI IT NL PL*	ES (Stellarator), (CH - Tokamak TCV)

NB: DE is only interested in aspects of safety of the fission systems where it appears

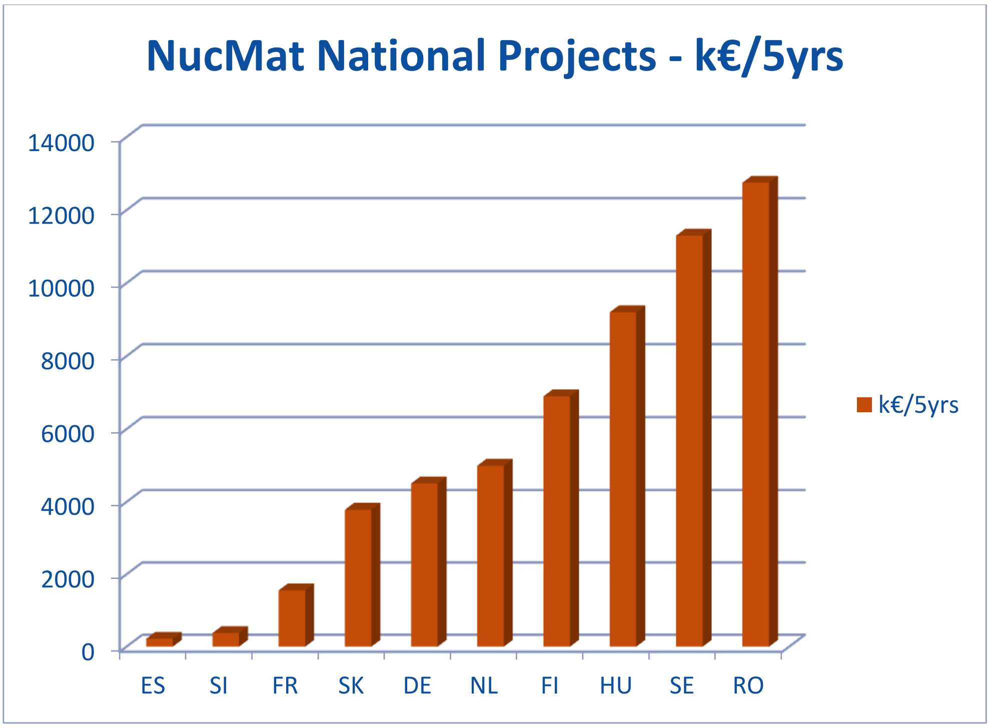
3) Main reasons to support financially research on NE and NM in particular (trying to rationalize scattered types of replies)**:**

[3] BE, BG, CH, CZ, DE, ES, FI, FR, HU, IT, NL, PL, RO, SI, SK
[4] Armenia became associated country of the EU on the 1st of March 2021 (The EU and Armenia Comprehensive and Enhanced Partnership Agreement enters into force https://ec.europa.eu/commission/presscorner/detail/en/ip_21_782)

Reason	MS/AC
Support (expanding) nuclear energy programme	BG CZ FI HU RO
Guarantee and increase safe operation of reactors, whether it is normal operation, LTO or new builds, also through improved assessments of aging and integrity	DE ES FI FR *HU* RO SK (CH)
Strengthen supply chain and quality of components	FR
Close fuel cycle – Design next generation reactors	FR RO
Digital innovation through materials health monitoring (NDE) and digital twins	FR
Maintain/expand competences: education, training and competence building of nuclear professionals	DE ES FR NL RO SK (CH)
Valorize existing or future nuclear materials research infrastructures	NL
Decommissioning and waste management	DE ES SK

4) National or Regional Funding to Projects between 2015-2020:

Summing up the declared budget associated with projects funded by national or regional agencies or industries, which by request covered the years from 2015 to 2020, excluding H2020 projects and fusion projects (when declared), the result from the survey is definitely surprising, see graph here below (Switzerland is out of graph with 45000 k€/5yrs): this result is likely the consequence of incomplete information obtained through the questionnaire.



The focus of national projects that have been declared in the questionnaire is the most diverse, although NDE and monitoring in general, SCC, and, partially, RPV or concrete related subjects, seem to dominate. The RO programme is for more than 90% focused on CANDU, quite obviously since they are the only ones in Europe using this reactor, so they cannot rely on EU money at all (the rest is LFR).

SE – SUNRISE: SUNRISE (Sustainable Nuclear Energy Research In Sweden) is the first step towards building a lead-cooled research and demonstration reactor in Sweden. Within the SUNRISE project design, safety analysis and materials development and qualification for a lead-cooled research reactor intended to be constructed in Oskarshamn is carried out. The project partners are KTH, Luleå University of Technology and Uppsala University. SUNRISE is funded with 50 MSEK by the Swedish Strategic Research Foundation and is co-ordinated by Professor Pär Olsson at the division of nuclear engineering at KTH.

5) About decommissioning:

Is there a roadmap?
Yes: BE BG CZ DE ES FR RO SK SE
No: HU SI
No answer: CH IT PL

Does it include materials (among those with roadmap)**?**
Yes: CZ, FI, FR (characterization, minimization of waste, recycling), SK, SE
No: BE BG DE RO (ES under discussion)

6) Possible synergies with nuclear materials in other nuclear related or non-nuclear fields if any:

National Cyclotron Centre (BG), materials in harsh environments + advanced manufacturing (industrial installation for large components) (FR), compact neutron sources (HU), medical applications (isotope production) (NL, ES) , materials for irradiation facilities or use of these for materials (FR, SK, ES, SE).

Referencias

[1] National Energy and Climate Plans, available at: https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

[2] WNA Country Profiles: https://world-nuclear.org/information-library/country-profiles.aspx

[3] IAEA Country Nuclear Power Profiles: https://www.iaea.org/publications/13448/country-nuclear-power-profiles

[4] Generation IV International Forum: https://www.gen-4.org/gif/

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

[6] Nuclear energy in the European Union: https://world-nuclear.org/information-library/country-profiles/others/european-union.aspx

[7] Estonia plans to build Europe's first small scale nuclear reactor: https://www.euractiv.com/section/politics/short_news/estonia-plans-to-build-europes-first-small-scale-nuclear-reactor/.

[8] Nuclear power could be an option for Ireland as smaller, safer reactors become available: https://www.irishexaminer.com/news/arid-40324322.html.

[9] A life extension to 80 years approved for the two units in Surry nuclear power plant in the United States: https://www.foronuclear.org/en/updates/news/a-second-20-year-extension-has-been-approved-for-the-two-units-in-surry-nuclear-power-plant-in-the-united-states/

[10] Questions and Answers at the NRG webinar on LTO, 4 November 2021, available at: http://www.eera-jpnm.eu/orient-nm/filesharer/documents/Useful%20Reference%20Documents

[11] Synthesis report on the aggregate effect of INDCs, United Nation Framework Convention on Climate Change, FCCC/CP/2016/2, 2 May 2016, https://unfccc.int/process/the-paris-agreement/nationally-determined-contributions/synthesis-report-on-the-aggregate-effect-of-intended-nationally-determined-contributions, Figure 2: Comparison of global emission levels in 2025 and 2030 resulting from the implementation of the INDCs and under other scenarios: https://unfccc.int/files/focus/indc_portal/image/jpeg/fig2exec_syr_update_v27apr2016_905_withlegend.jpg

[12] https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum.

[13] Nascent hydrogen market needs low-carbon nuclear power: EU official: https://www.euractiv.com/section/electricity/news/nascent-hydrogen-market-needs-low-carbon-nuclear-power-eu-official/

[14] The Future of Hydrogen - Seizing today's opportunities, IEA Technology report — June 2019: https://www.iea.org/reports/the-future-of-hydrogen

[15] E. Hanus, NUWARDTM, SNETP Forum 2021: https://snetp.eu/wp-content/uploads/2021/02/Presentation_Eric-HANUS.pdf

[16] Nuclear Hydrogen Production Technology: https://www.iaea.org/sites/default/files/gc/gc57inf-2-att1_en.pdf

[17] First small nuclear reactor in Finland in 10–15 years? https://www.fortum.com/about-us/blog-podcast/forthedoers-blog/first-small-nuclear-reactor-finland-10-15-years

[18] Romania, Bulgaria intend to build small nuclear power plants: https://balkangreenenergynews.com/romania-bulgaria-intend-to-build-small-nuclear-power-plants/

[19] Policy paper - Advanced Nuclear Technologies - Updated 7 March 2022: https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies

[20] A Ukrainian Roadmap for Small Modular Reactors: Current Activities and Future Plans: https://nucleus.iaea.org/sites/htgr-kb/twg-smr/Documents/TWG-2_2019/B09_Ukrainian%20Roadmap%20for%20SMRs.pdf

[21] LeadCold: https://www.leadcold.com/

[22] Hydromine Nuclear Energy Sarl: https://aris.iaea.org/PDF/Hydromine%20LFR-AS-200_2020.pdf

[23] Development of versatile liquid metal testing facility for lead-cooled fast reactor technology: https://gtr.ukri.org/projects?ref=EP%2FT003359%2F1

[24] Westinghouse Lead Fast Reactor Design and Safety: https://inis.iaea.org/collection/NCLCollectionStore/_Public/52/041/52041030.pdf

[25] Tarantino, M.; Angiolini, M.; Bassini, S.; Cataldo, S.; Ciantelli, C.; Cristalli, C.; Del Nevo, A.; Di Piazza, I.; Diamanti, D.; Eboli, M.; et al. Overview on Lead-Cooled Fast Reactor Design and Related Technologies Development in ENEA. Energies 2021, 14, 5157. https://doi.org/10.3390/en14165157.

[26] Climate change worries fuel nuclear dreams: https://www.politico.eu/article/climate-change-nuclear-power-plants-energy

[27] MYRRHA - Multi-purpose hYbrid Research Reactor for High-tech Applications: http://roadmap2018.esfri.eu/projects-and-landmarks/browse-the-catalogue/myrrha/

[28] Accelerator-driven Nuclear Energy: https://world-nuclear.org/information-library/current-and-future-generation/accelerator-driven-nuclear-energy.aspx.

[29] Denmark's Seaborg Attracts Private Funding For Molten Salt Reactor Project: https://www.nucnet.org/news/denmark-s-seaborg-attracts-private-funding-for-molten-salt-reactor-project-11-5-2020.

[30] Rethinking Nuclear: https://www.seaborg.com/

[31] Mass manufacturing thorium reactors: https://www.copenhagenatomics.com

[32] Dutch consortium set up to develop of molten salt reactors: https://www.neimagazine.com/news/newsdutch-consortium-set-up-to-develop-of-molten-salt-reactors-8566820

[33] J. Uhlíř & V. Juříček, (2016). Current Czech R&D in Thorium Molten Salt Reactor (MSR) Technology and Future Directions. In: Revol, JP., Bourquin, M., Kadi, Y., Lillestol, E., de Mestral, JC., Samec, K. (eds) Thorium Energy for the World. Springer, Cham. https://doi.org/10.1007/978-3-319-26542-1_20.

[34] The concept of Molten Salt Fast Reactor (MSFR): Molten Salt Reactor with a Fast Neutron Spectrum: https://lpsc.in2p3.fr/index.php/en/106-groupes-de-physique/msfr

[35] F. Gauché. Generation IV reactors and the ASTRID prototype: Lessons from the Fukushima accident. C. R. Phys. 2012, 13, 365–371. https://doi.org/10.1016/j.crhy.2012.03.004

[36] G. Rodriguez, *et al*. The knowledge management on the design of a generation IV sodium fast reactor project at CEA. The case and methodology applied on the Astrid project. EPJ Nuclear Sci. Technol. 6, 53 (2020). https://doi.org/10.1051/epjn/2020016

[37] Possibilities for deployment of high-temperature nuclear reactors in Poland: https://www.gov.pl/attachment/ccc29947-3858-4b95-9cf5-88eefb8a240b

[38] High Temperature Gas Cooled Reactor Technology Development, IAEA-TECDOC-988, 1998: https://www.iaea.org/publications/5643/high-temperature-gas-cooled-reactor-technology-development

[39] G. Wrochna, M. Fütterer, D. Hittner (2020). Nuclear cogeneration with high temperature reactors. European Physical Journal N (Nuclear Science & Technologies), 6 (1), 31. https://doi.org/10.1051/epjn/2019023.

[40] Preparation of ALLEGRO—Implementing Advanced Nuclear Fuel Cycle in Central Europe. Available online: https://cordis.europa.eu/project/id/323295/reporting/es

[41] B. Kvizda, et al. (2019). ALLEGRO Gas-cooled Fast Reactor (GFR) demonstrator thermal hydraulic benchmark. Nuclear Engineering and Design 345, 47-61. https://doi.org/10.1016/j.nucengdes.2019.02.006

[42] ALLEGRO development team: https://www.ujv.cz/en/akordeonovy-seznam/allegro-development-team-11796

[43] https://ecc-smart.eu/

[44] Generation IV International Forum: https://www.gen-4.org/gif/

[45] UK Government Chooses High-Temperature Gas-Cooled Reactors (HTGRs) For Advanced Modular Reactor Programme: https://x-energy.com/media/news-releases/uk-government-chooses-high-temperature-gas-cooled-reactors-htgrs-for-advanced-modular-reactor-programme

[46] Halden Reactor Project: https://www.oecd-nea.org/jcms/pl_24970/halden-reactor-project.

[47] Serbia mulls construction of its own nuclear power plant: https://balkangreenenergynews.com/serbia-mulls-construction-of-its-own-nuclear-power-plant/

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