NUCLEAR DEVELOPMENT SCENARIOS IN THE CONTEXT OF CLIMATE POLICIES AND DEVELOPMENT OF DISRUPTIVE TECHNOLOGIES

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Abstract

To explore the role of nuclear power in the future development of society a several scenarios were built. The methodology involved the identification of key energy demand drivers, generation of a variety of alternative scenarios, checking plausibility and consistency, and constructing associated narratives. The complexity resulting from the long-term perspective, the numerous parameters and their associated uncertainties (e.g., those related to evolutions of the key parameters)is approached by progressive simplification. By considering the most relevant influencing factors and their variability, a set of four scenarios was retained: Nuclear Status Quo (unchanged pace of nuclear development, not much influenced by an acceleration of renewables); Nuclear Phase-Out (no new nuclear project, progressive phase-out); Nuclear and Renewables Synergy (nuclear development to support accelerated implementation of renewables), and Nuclear Renaissance (the nuclear share accelerated by the development of new reactor technologies). Considerations for each scenario are discussed in order to offer the basis for projections and deliberations in the policy decision-making process.

Keywords: *Nuclear energy, Scenarios, Net zero emissions, Sustainability, Strategic development*

Introduction

Energy scenarios are alternative views of future energy development. The scenario method has been widely used in different decision analytic areas such as the general development of economy or society, in business, technology, energy foresight, etc. It is considered to be ″an unrivalled technique to learn about the future before it happens″ [1]. Scenarios may be used for exploratory purposes, for example to identify the implications of different assumptions and understand possible pathways to build a future in accordance with societal expectations. In other situations, normative scenarios are defined to orient development in alignment with strategies and policies.

The paper presents the construction of nuclear development scenarios, for the European Union (EU) at horizon of 2050, by considering climate policy implementation and possible evolutions of some disruptive technologies (such as AI, advanced robotics, nanotechnologies, biotechnologies, additive manufacturing, block chain, or drones). The scenario building takes into account the EU's vision of development in the context of the Green Transition, projections on energy demand, and possible medium- and long-term evolutions in energy technologies.

In the frame of Euratom ECOSENS project (Economic and Social Considerations for the Future of Nuclear Energy in Society) [2], a full life cycle sustainability assessment of current nuclear energy technologies is in progress. A new methodology [3] was developed in view of producing a fair comparative assessment of sustainability performances for the current energy alternatives. Possible changes in society and the energy sector were investigated, in order to create a basis for the identification of the possible future roles of nuclear energy [4].

Regarding the energy sector, the future context of the EU is taken as described by the elements of the Net Zero Emissions (NZE) scenario [5]. NZE is a normative scenario, used to drive the EU region towards some specific objectives. However, even if the normative scenario is strongly supported by policymakers, actual societal and technological evolutions may drift implementation towards more pragmatic actions.

The current paper develops a set of scenarios with the aim to provide decision makers with a reliable and neutral basis for exploration. So-called exploratory scenarios have more flexibility and are frequently used in support of long-term decisions. Examples include the *Jazz and Symphony scenarios* developed by World Energy Council (WEC) [6] which address environmental sustainability, energy security, and energy equity. The *Jazz scenario* is oriented mainly to the achievement of individual access and affordability of energy through economic growth, whereas *Symphony scenario* is focused on environmental sustainability through internationally coordinated policies and practices [6].

The ECOSENS scenarios presented in this article offer a structured approach to navigate the complexities of an uncertain future, supporting the management of risks, and allowing organizations and individuals to reflect in more detail on the energy issues and on the impacts of possible evolutions of society and technologies.

Methodology

The construction of the scenario, referred to as *scenario building*, is a strategic planning method based on the analysis and understanding of the current situation, of historical trends, and of existing predictions/projections of the future. Consistent descriptions of possible evolutions must be developed to illuminate potential pathways towards the future. Checking and reinforcing the plausibility of these pathways transforms them into useful scenarios. An exploration of the associated uncertainties is necessary to increase confidence in the defined scenarios.

The key steps in the scenario building process are shown in Table 1. The primary list, presented in Table 2, is quite extensive and an effort to reduce it to the most influential factors was done.

Table 1. Key steps in the scenario building process

	Key step	Description of activity
0	Baseline situation	Formulate the present-day situation or theoretical starting point of the decision area under consideration.
1	Identification of key drivers	Identify relevant influencing factors (technological, social, economic, etc.) which may have significant impact on future evolutions. (The outcome is described in [4].)
2	Defining the alternative scenarios	Generate a set of scenarios based on different combinations of relevant influencing factors impacts, and considering logical extrapolations of current trends or plausible disruptions.
3	Checking plausibility and consistency	Check the internal consistency and plausibility of each scenario, including extreme or unlikely situations, and introduce corrections if needed.
4	Narrative construction	Create detailed narratives, describing the possible futures, easily visualized and understood, including information on how the influencing factors shape the scenarios.
5	Iterative process	Update scenarios in case of any new available information or changing of circumstances.
6	Testing	Test scenario resilience across multiple future conditions to understand how the scenario will perform in a strategic planning process. (Return to step 5 if indicated.)
7	Use	Organizations and decision makers explore possible impacts of their strategies and plans in context of different scenarios to identify vulnerabilities, opportunities or needs for change.

Table 2. List of factors influencing the development of the energy sector

1.	Demographic	1.1 Size of population
		1.2 Structure of ageing
		1.3 Potential labor force and participating labor force
		1.4 Urbanization
		1.5 Migration
		1.6 Healthcare expenditure
2.	Economic	2.1 GDP (Gross Domestic Product; overall and per capita, growth rate)
		2.2 Distribution of GDP per sectors and subsectors
		2.3 Investment and capital accumulation
		2.4 Savings versus investments
		2.5 Financial environment
		2.6 Globalization
		2.7 Crisis (economic and financial, geopolitics, migration, public health)
3.	Technological	3.1 Energy intensity (average and per sectors)
		3.2 Disruptive technologies
		3.3 Productivity
		3.4 Decentralization of energy production
		3.5 Massive electrification (transportation, heat)
		3.6 Improvements in intermittent energies (efficiency, siting, use of resources)
		3.7 Development of large storage capacities
		3.8 Improvements in the interconnections of energy systems
4.	Environment	4.1 Resources depletion (availability for future generations)
		4.2 Discovering new resources or improving extraction efficiency
		4.3 Pollution problems and their effect on health
		4.4 Climate change mitigation and adaptation
		4.5 Development of a sustainable food model
		4.6 Sustainable urban development and mobility
		4.7 Energy taxes
5.	Social and cultural	5.1 Decentralization of production by a large presence of the prosumers
		5.2 Changes in occupational structure
		5.3 New approaches to aggregate groups and community (post information society)
		5.4 New ways to build decisions (influence of algorithms)
		5.5 Role of cyborgs (half-human, half-machine creatures)

To reduce the investigation complexity, this set of 33 factors was reduced to 12 key drivers, based on discussions organized inside ECOSENS with a group of stakeholders [7, 8]. The key drivers are given in Table 3. For each of them, the possible influence is described by three levels of impact (High, Medium, Low). However, considering the likely strong influence of climate policies (e.g. an optimistic pursuit of the NZE normative scenario) and to simplify, the Decarbonization, Grid modernization, Interconnectivity, Resilience and adaptation, and Global cooperation drivers are defaulted to High impact. Carbon capture and storage factor's is credited with Medium impact, due to the quite modest progress observed today in the deployment. These simplifications have reduced the number of scenarios, but not enough, since varying the key factors from Table 3 results in $3^6 = 729$ scenarios.

Table 3. Scenarios associated with the evolution of the key influencing factors

	Key factor	Associated scenarios		
1	Decarbonization	High		
2	Renewable energy	High	Medium	Low
3	Electrification	High	Medium	Low
4	Energy storage	High	Medium	Low
5	Energy efficiency	High	Medium	Low
6	Behavioral changes	High	Medium	Low
7	Grid modernization	High		
8	Interconnectivity	High		
9	Resilience and adaptation	High		
10	Carbon capture and removal	Medium		
11	Technological advancements	High	Medium	Low
12	Global cooperation	High		

A further simplification is needed to reduce this complexity since in common practice only a few scenarios are retained to support a focused vision of the decision-makers.

An exploration of the six key factors with variable impact (High, Medium, Low) is presented in detail in [9]. All of them impact the energy demand and energy mix influencing the possible roles for nuclear energy in the future. For example, high implementation of renewables will reduce the competitive advantages of nuclear power (price affordability) whereas a high level of electrification (shifting to electrical heating, electric vehicles) will stimulate nuclear development. A high implementation on energy efficiency and a high development of large-scale storage will reduce the needs for baseload power, therefore deployment potential of nuclear. A behavioural shift from energy consumers to prosumers, or even drastically reducing of energy wastage may decrease the need for new nuclear units. For the technological advancements the situation is more complex, with pros and cons to the stimulation of nuclear development.

Efforts were focused on identification of a limited set of nuclear power scenarios covering representative cases.

Nuclear power scenarios

Considering the context of the climate neutrality in the EU, with the current orientations in favour of massive electrification, widespread implementation of energy efficiency measures, and high penetration of renewable energy sources (RES) in electricity production, four plausible scenarios for the evolution of the nuclear power are defined, as can be seen in Table 4.

Table 4. Scenarios and sub-scenarios for nuclear power, in the medium and long-term

Scenario	Description	Sub-scenario
Nuclear Status Quo (NSQ)	Nuclear keeps its present pace of development, not much influenced by acceleration of RES, but driven by energy security, economics and diversification of energy sources	-
Nuclear Phase-Out (NPO)	Progressive phase-out, long-term operation (LTO) of existing plants (or not, in certain national circumstances), implementation of projects with already approved investment, no other new nuclear project	(NPO1) Fast phase-out (in the short term, under anti-nuclear vision, horizon 2040-2050)
		(NPO2) Moderate and progressive phase-out (horizon 2050-2060)
		(NPO3) Slow phase-out (no new build, phase-out by end of life of the existing NPPs)
Nuclear and Renewables Synergy (NRS)	Nuclear to support accelerated implementation of RES (security of energy, backup, balance)	(NRS1) Energy mix is dominated by RES, followed by nuclear (baseload mode), using predominantly gas to balance peak consumption
		(NRS2) A combination of RES (predominantly) with nuclear for security of supply and thermal storage
		(NRS3) Predominant use of RES will be supported by nuclear (baseload) and storage using batteries, thermal storage, and hydrogen production
Nuclear Renaissance (NR)	Nuclear accelerated by new technologies (SMR and GenIV)	(NR1) Accelerated development of nuclear in the short term (imposed by climate urgency)
		(NR2) Nuclear development boosted by successful implementation of SMRs (2025-2050)
		(NR3) Preparation of nuclear development in the long term (after 2050) by new generation systems (advanced SMR and GenIV)

The first scenario, *Nuclear Status Quo* (NSQ), supposes a continuation of the current trend of nuclear deployment, with a group of countries determined to build new NPPs, while some other countries decide to phase-out. The second scenario, *Nuclear Phase-Out* (NPO), is the pessimistic scenario, supposing a gradual closure of all NPPs. Three sub-scenarios are defined based on the speed of the phase-out. The third scenario, *Nuclear and Renewables Synergy* (NRS), supposes that nuclear power and renewables will be deployed in a complementary manner. Three sub-scenarios are defined for NRS based on the approach to ensuring peak supply. The last scenario, *Nuclear Renaissance* (NR), is the optimistic scenario for nuclear and supposes accelerated development of small modular reactors (SMRs) and GenIV systems. Three NR sub-scenarios were developed to take into consideration different rates and periods of acceleration.

In the following some details for the scenarios and sub-scenarios are presented.

NSQ scenario

This status quo scenario considers that nuclear power will remain an option for the current pro-nuclear group of member states of the European Union. The nuclear sector keeps its present pace of development, not much influenced by the accelerated process of implementing RES (especially photovoltaic and wind power). The NSQ scenario is driven by energy security, economics and diversification of energy sources.

This scenario envisions the EU maintaining its existing nuclear power capacity, without significant growth or decline. The existing NPPs, which have been in operation for several decades, continue to provide a significant amount of the EU's electricity generation. Phase out remains possible in a few nuclear countries, those already engaged in such a process. The reduction in nuclear capacity will be compensated at EU level by new nuclear investment, especially in the Central and Eastern European (CEE) region.

Long-Term Operation (LTO) will be engaged for most NPPs, typically extending operational lifetime beyond the originally designed period of 40 years to up to 60 years or more. This extension is achieved through rigorous safety assessments, equipment upgrades, and maintenance to ensure the continued safe and efficient operation of the plant. LTO aims to maximize the economic and environmental benefits of existing nuclear infrastructure while meeting strict safety and regulatory requirements.

After the extended LTO period the older nuclear power plants will be gradually decommissioned and safely dismantled. Nuclear waste from these plants will be managed and stored in accordance with established safety protocols, although there is no significant investment in advanced waste management technologies.

In the NSQ scenario, the EU continues to pursue its emissions reduction targets and the role of nuclear power in meeting these targets remains relatively stable. Nuclear energy complements intermittent renewable sources by providing constant baseload power with low carbon emissions. While nuclear energy remains a stable and reliable source of electricity, the EU member states in this scenario will diversify their energy mix. Renewables, particularly wind and solar, will play an increasingly significant role in electricity generation, with additional investments in natural gas and possibly some fossil fuels to provide peak and backup power.

The NSQ scenario economic feasibility depends on e.g. the cost of maintaining existing nuclear plants, renewable energy development costs, and energy market dynamics. Energy prices may vary depending on the evolutions of the fuel costs and government policies. Significant investment will be needed to upgrade the electricity grid to better integrate nuclear power and accommodate fluctuations in electricity supply from renewable sources. Smart grid technologies and energy storage solutions will be developed to manage grid stability.

The NSQ scenario provides a level of energy security, as nuclear power offers a stable source of electricity. The EU here is less reliant on energy imports compared to scenarios where nuclear energy is phased out.

In the NSQ scenario research and innovation will be primarily focused on safety improvements, operational efficiency, and waste management, rather than on substitution of innovative technologies and expansion.

NPO scenario

This scenario is described by a gradual phase-out of NPPs, considering a LTO process limited to some of the existing plants and restricting the nuclear investment to the advanced planned project (NPP already having a firm commitment for investment).

Opponents of nuclear power who support its phase-out typically envision a future where energy production is based on sources considered more sustainable, with a strong emphasis on minimizing the environmental, safety, and proliferation risks. Their vision often includes a gradual transition away from nuclear power in favor of alternatives that align with green visions.

In NPO scenario, a majority of EU member states decide to phase out their nuclear power plants by 2050-2060 influenced by the concerns about nuclear safety, nuclear waste disposal, and public opinion against nuclear energy. A gradual decommissioning of existing plants is supposed, with the consequence of a decreased role of nuclear energy in the EU energy landscape by 2050. Some variants in terms of the decommissioning speed are embedded in the three formulated sub-scenarios:

- *(NPO1) Fast phase-out* (on short term, following anti-nuclear vision, to be reached in 2040-2050)
- *(NPO2) Moderate phase-out* (progressively to be reach in 2050-2060)
- *(NPO3) Slow phase-out* (no new built, phase out by end of life of the existing NPPs).

The process of nuclear phase-out involves a series of steps to gradually reduce or eliminate the use of nuclear power as an energy source. The nuclear facilities will be retired at the end of their operational lifespan or sooner, and no new NPPs will be constructed. For some countries a phase-out of a nuclear reactor before its end of life is possible according with the national policies.

The specific steps and timeline may vary by country and depend on political, economic, and environmental factors. The first step is a political decision to phase out nuclear power. This may involve legislative changes or a government commitment to stop building new nuclear reactors and gradually decommission existing ones. The second step consists of the development of a comprehensive energy transition plan that outlines how the country will replace nuclear power with alternative energy sources, energy efficiency measures, or reduction of the consumption. A revision of the regulations and policies to accommodate the phase-out process should be necessary in the most national frameworks. Then, a plan for decommissioning nuclear reactors that includes the safe shutdown of reactors, dismantling of infrastructure, and dealing with radioactive waste has to be developed. The nuclear reactors shutdown is followed by the decommissioning process, which can take several decades to complete. This involves dismantling of facilities, decontamination of sites, and managing radioactive waste ensuring safe storage and disposal solutions for all radioactive materials.

From the point of view of the social aspects, programs to support workers and communities affected by the phase-out, such as retraining programs for nuclear industry workers and economic development initiatives in regions previously dependent on nuclear energy, have to be implemented.

During the phase-out process a continuously monitoring of the progress, safety of decommissioned sites, and transition to alternative energy sources is necessary. Finally, the evaluation step will officially complete the phase-out process by evaluating the success of the transition, and make any necessary adjustments to energy policies and strategies.

The economic feasibility of the nuclear phase-out scenario depends on the alternative energy sources affordability and reliability. In NPO scenario, achievement in the RES implementation has to be at High level in order to ensure the necessary installed capacity taking into consideration the effect of usual intermittency in electricity generation. Such development introduces important costs for grid integration in order to ensure security of supply, and government incentives through programs that promote renewable energy adoption, such as tax credits. The price of electricity may become more variable due to the intermittency of renewables, affecting energy costs for consumers and industries. Government interventions may be necessary to stabilize prices.

With the phase-out of nuclear power, concerns about energy security arise. The EU will become more dependent on energy imports, particularly in the absence of domestic nuclear generation. Efforts are needed to diversify energy sources and reduce reliance on a single energy supplier or fuel.

The development of performant and environment friendly energy storage systems (to store excess energy during periods of high renewable energy generation and use it when generation is low), together with energy efficiency measures has to be at High level. In NPO scenario one of the key actions for climate policy, the electrification, should be reduced to Moderate or even Low level in order to balance the generation and consumption of electricity.

Adapting to an energy variable regime requires a combination of consumer education, technological solutions, and policy support to make the transition to a more sustainable and flexible energy system. Consumers can play a vital role in helping balance energy supply and demand in a world increasingly reliant on renewable energy sources. High changes in the habits of consumers are postulated in NPO scenario, in favor of the reduction of the consumption, flexible energy use (consumers can adopt a more flexible approach to using energy-intensive appliances and activities, for example running them during times when renewable energy generation is high), and demand response programs (offered by utilities, which encourage consumers to reduce or shift their energy usage during peak demand periods or when renewable energy generation is low).

A fast phase-out of nuclear power (NPO1 sub-scenario) in the European Union energy system can pose several risks and challenges:

(1) energy supply disruptions and grid instability, especially if alternative sources of energy are not sufficiently developed to replace the lost capacity
(2) energy prices (a sudden drop in nuclear power capacity can lead to higher energy prices due to increased demand for alternative energy sources, potentially impacting consumers and businesses)
(3) energy security (EU would become more dependent on energy imports, which could be subject to geopolitical and supply risks).
(4) loss of low-carbon energy (phase-out can slow down progress toward decarbonization, especially if nuclear power is replaced by fossil fuels or high-emission energy sources due to the difficulty to support a fast development of renewables).
(5) waste management (an accelerated phase-out could complicate radioactive waste management and disposal, as decommissioned plants may not be fully prepared for shutdown, and storage facilities may need to be expanded more rapidly)
(6) investment and financing challenges (rapid changes in the energy landscape can deter investment in long-term energy projects, investors may be hesitant to invest in alternative energy sources without a stable regulatory and market environment)
(7) job displacement (fast phase-out may result in job displacement without adequate plans for retraining and transition support for affected workers).

NRS scenario

The scenario is characterized by nuclear development to support accelerated implementation of RES based on its excellent features in security of supply, backup, and grid balance.

This scenario envisions a balanced approach where the EU combines nuclear and RES to achieve its climate goals. Member states invest in maintaining their current nuclear power capacity while also expanding renewable energy infrastructure. RES, such as solar or wind, generate electricity in certain weather conditions (i.e., on sunny or windy days), while nuclear power provides a consistent baseload supply to fill in gaps.

Nuclear power will continue to play a significant role in the EU's energy mix. Existing NPPs will be well-maintained and safely operated. Member states may also invest in the construction of next-generation nuclear reactors, such as SMRs and advanced reactors, including fast reactors. These new reactors are designed to be safer, more efficient, and capable of using recycled nuclear fuel, reducing nuclear waste concerns.

In terms of RES, the EU experiences substantial growth, particularly wind and solar power. Member states continue to invest heavily in RES infrastructure, including onshore and offshore wind farms, solar arrays, and hydropower facilities. Advanced energy storage technologies, such as large-scale batteries, hydro accumulation, hydrogen generation, or thermal energy storage are developed to manage intermittent renewable energy generation and ensure a stable power supply.

NRS is characterized by a High electrification, High renewable share, and is compatible with High energy efficiency. Three sub-scenarios are defined to describe the possible energy mixes in the NRS:

- (NRS1) The mix will be dominated by RES, followed by Nuclear (base load mode), and using dominantly gas for the balancing of peak consumption
- (NRS2) A combination of RES (dominantly) with nuclear for security of supply and thermal storage
- (NRS3) Dominantly RES will be supported by nuclear (base load) and storage using batteries, thermal storage and hydrogen production.

The synergies between nuclear and renewables can play a crucial role in achieving a more sustainable and diversified energy system. The low-carbon capability of renewables is amended by the intermittency. During the periods with low renewable production or with high energy demand, back up sources will be used based especially on gas (even on coal) with important effect in the raise of the emissions. On the other hand, even in case of modern gas plant, the operation in peak-load regime introduces more emissions due to the working in a non-optimal regime. A baseload nuclear production provides stability complementing the intermittent nature of renewables, such as wind and solar power. Nuclear energy can fill in the gaps when renewable sources are not producing electricity, ensuring a continuous and low-carbon energy supply. The combination of nuclear and renewable energy sources can significantly reduce carbon emissions. By relying on both low-carbon nuclear power and renewables, the EU can make substantial progress in meeting its climate goals.

In terms of energy security, nuclear power can enhance energy security by reducing reliance on fossil fuel imports. This, in turn, can complement the EU's efforts to diversify its energy sources and reduce exposure to energy supply disruptions.

Even the current nuclear plants are offering a limited flexibility in the electricity production (restricted to power ramp's speed and number of material cycles, and constrained by reactivity effects), there are advanced nuclear reactor designs allowing them to ramp up and down more quickly to complement intermittent renewable generation. A great improvement may be introduced by the energy storage development and implementation.

For nuclear power the most appropriate storage is of the thermal energy involving the capture and storage of excess heat produced by nuclear reactors for later use. This process helps enhance the efficiency and flexibility of nuclear plants. There are various methods for thermal energy storage in the context of nuclear power: molten salt storage, concrete storage, bedrock storage, high-temperature steam accumulators, phase change materials, underground thermal storage.

The thermal storage allows nuclear plants to better match electricity production with fluctuating demand, reducing the need for load-following or cycling of the reactor. It can enable the integration of nuclear power with renewable energy sources, as the stored heat can supplement intermittent renewables when needed. It can improve the overall efficiency of the nuclear plant by optimizing the operation of the heat-to-electricity conversion process.

For the intermittent RES, the batteries are seen as the most convenient storage. The current development of batteries used to store electricity has made significant progress, but it also faces several challenges and issues that need to be addressed for further improvement and widespread adoption: low energy density, high environmental impact, life cycle and durability, safety (thermal runaway and the risk of fires or explosions), duration of charging, recycling issues, resource availability(most of batteries rely on lithium, cobalt, and nickel, with supply chain limitations and environmental concerns), grid integration (integrating large-scale battery storage into the electrical grid is complex requires advanced control systems, grid infrastructure upgrades, and regulatory changes), costs.

An alternative option to the energy storage is the hydrogen production for grid balance, also known as grid-scale hydrogen production. It involves producing hydrogen using various methods and technologies that can be used to store excess energy when there is an oversupply of electricity on the grid and release it when there is a high demand. This helps stabilize the grid, promote renewable energy integration, and ensure a reliable and resilient energy supply.

Considering the NRS scenario, due to the significant development of nuclear to cope with RES variable production, in some configurations waste heat from NPPs can be used for district heating or other industrial applications, increasing overall energy efficiency.

In terms of the transition planning to a more sustainable energy system, existing nuclear infrastructure can provide a bridge while RES capacity is scaled up, helping ensure a smooth energy transition. Some synergies are possible in the research and innovation by approaching grid integration, energy storage, and energy efficiency.

In the scenario, public opinion remains relatively stable in favor of nuclear energy due to the strong safety record of advanced nuclear technologies and the importance of nuclear power in achieving climate goals. The public is generally supportive of renewables, which are seen as clean and sustainable sources of energy.

The NRS scenario economic feasibility is supported by the combination of stable, long-term baseload power from nuclear energy and decreasing costs of renewable energy technologies. Energy markets are structured to incentivize use of low-carbon technologies, ensuring a sustainable and affordable energy supply for EU citizens and industries.

NR scenario

The NR (Nuclear Renaissance) scenario envisions a renewed and expanded role for nuclear energy in the European Union (EU) context by 2050. In this scenario, there is a strong emphasis on nuclear energy as a key pillar of the EU's energy strategy. The development of nuclear is accelerated by the new technologies (SMR and GenIV).

In this scenario, the EU experiences a renewed interest in nuclear energy. Member states invest in the construction of new NPPs, with advanced safety features and technologies. Strict emissions reduction targets and energy security concerns drive the expansion of nuclear energy. The EU places a strong emphasis on research and development for next-generation nuclear technologies, such as SMRs and GenIV reactors. Nuclear power becomes a significant contributor to achieving carbon neutrality by 2050. The expansion of nuclear energy is driven by the EU's ambitious emissions reduction targets and the need to combat climate change. Nuclear power is seen as a crucial component of achieving carbon neutrality by 2050. It provides a stable, low-carbon baseload power source to complement intermittent renewables.

In NR scenario the level of electrification is considered as High, whilst the development of renewables is Medium or Low, and the energy storage is at Medium level. Three sub-scenarios are defined to describe the different options for the NR scenario:

- (NR1) Accelerated development of nuclear on short term (imposed by climate urgency)
- (NR2) Nuclear development boosted by the successful implementation of SMRs in the next decades
- (NR3) A nuclear development prepared for long term (after 2050) by new generation systems (advanced SMR and Gen IV).

In terms of the new NPPs, the EU member states make significant investments in the construction of new reactors equipped with the latest safety features and technologies to address public safety concerns and ensure the highest level of security. New nuclear power plants are strategically located across the EU to meet regional energy needs.

The RES development is considered moderate due to the insufficient rate of implementation (difficulties in expansion, supply chains, materials), not successful improvement of the performances (investment and grid integration costs), slowing-down of the initial enthusiasm in the positive impact in climate change prevention and mitigation.

Development of the next-generation nuclear technologies is a factor stimulating the appropriate conditions for the NR scenario. This includes development and deployment of SMRs, which are more flexible, modular, and safer than traditional large reactors. GenIV reactors and other advanced reactor designs are explored to diversify nuclear options and reduce nuclear waste.

The development of new systems will enhance the sustainability performances of the nuclear power. For example, significant developments in advanced nuclear waste management solutions, including reprocessing and recycling technologies, are supposed in NR. This reduces the nuclear waste volume, minimizes the need for long-term storage, and addresses concerns about radioactive waste disposal.

The expansion of nuclear energy will enhance energy security in the EU. Nuclear power will be able to provide a stable and reliable source of electricity, reducing dependence on energy imports and vulnerabilities related to fluctuating fuel prices. A significant investment in upgrading the electricity grid to better integrate nuclear power and intermittent renewables is considered in the NR scenario. Smart grid technologies and energy storage solutions are developed to manage wind and solar energy variability, ensuring a reliable and resilient energy supply.

In terms of nuclear safety and public acceptance, strict regulatory measures are introduced to ensure the highest safety standards, and public education campaigns are conducted to dispel misconceptions about nuclear energy. Public opinion becomes more favorable as nuclear technology advances and demonstrates a strong safety record.

The economic feasibility of this scenario is supported by the long-term, low-carbon nature of nuclear power. It is considered a cost-effective way to generate clean energy and reduce greenhouse gas emissions. Government incentives and market mechanisms are designed to encourage private sector investment in the nuclear sector. The EU becomes a global leader in advanced nuclear technology and exports its expertise in nuclear energy to other regions. It engages in international collaboration to promote the peaceful use of nuclear energy, non-proliferation, and nuclear safety standards. The EU continues to invest in research and innovation to make nuclear energy even safer and more efficient. This includes advancements in reactor design, fuel technology, and waste management.

Conclusions

(C1) A classical methodology including the identification of key drivers, defining alternative scenarios, checking plausibility and consistency of the defined scenarios, and constructing narratives was used to define four realistic scenarios (including six sub-scenarios) for nuclear power in the EU at the horizon of 2050.

(C2) The nuclear power role is strongly influenced by the evolutions in the energy sector (especially the electricity demand), and by technological and market evolutions. A set of twelve key factors influencing the future energy scenarios was identified. The impact of each factor may be high, moderate, or low, depending on the evolutions of the EU context or circumstances. To reduce complexity, six of the key factors were considered to have a well-defined impact (generally High), in keeping with the normative scenario, NZE, developed to guide strategies and plans. The other six key factors may have a broader range of impact (High, Medium, Low). Despite simplifications, the complexity remains very high and the reduction to a reasonable number of scenarios was necessary.

(C3) The four scenarios defined were: *Nuclear Status Quo* (NSQ), *Nuclear Phase-Out* (NPO), *Nuclear and Renewables Synergy* (NRS), and *Nuclear Renaissance* (NR). NSQ is a continuation of the current tendency, not much influenced by an acceleration of renewables or by the competition with other technologies. NPO describes a gradual phase-out of nuclear power, with no new nuclear project. A gradual decommissioning of existing plants is supposed, with the consequence of a decreased role of nuclear energy in the EU energy landscape by 2050. NRS describes nuclear power development supporting the accelerated implementation of renewables in view of security of supply, large capacity production, predictability and stability, and affordability. The last scenario, NR, envisions a renewed and expanded role for nuclear energy as a major pillar of the EU's energy strategy. The development of nuclear is accelerated by the new technologies (SMR and GenIV). Considerations on the each scenario feasibility and on the favorable conditions to become reality are presented.

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