Economic and Social Considerations for the Future of Nuclear Energy in Society

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Contents

List of abbreviations and acronyms

AI Artificial intelligence

BEV Battery electric vehicle

CCS Carbon capture and storage

CEEC Central and East European Countries

EC European Commission

EPR European pressurized water reactor

ETS Emission Trading System

EU European Union

GDP Gross domestic product

GHG Greenhouse gas

GIV Generation or Gen IV (reactor)

GWe Gigawatt electric

IAEA International Atomic Energy Agency

ICEV Internal combustion energy vehicle

IoT Internet of things

IPCC International panel on climate change

LTO Long-term operation

MS Member state (of the European Union)

NPO Nuclear Phase-Out (scenario)

NPP Nuclear power plant

NPT Treaty on the Non-Proliferation of nuclear weapons

NR Nuclear Renaissance (scenario)

NRS Nuclear and Renewables Synergy (scenario)

NSQ Nuclear Status Quo (scenario)

NZE Net zero emissions

PV Photo voltaic

RDI Research, development, and innovation

RES Renewable energy source

SMR Small modular reactor

TWh Terawatt hours

U (reactor) Unit

UN United Nations

W Wind

Executive Summary

The ECOSENS project includes an assessment of the sustainability performance of the nuclear power for the entire life cycle considering the current development of nuclear technologies together with the investigation of the evolutions of the energy market in the transition toward climate neutrality in order to discuss the role of the nuclear power in the medium and long term.

In this deliverable, a set of scenarios for nuclear power development in the European Union at the horizon of 2050 was developed, based on the previous ECOSENS investigation of energy demand, existing policies for decarbonization, and impact of societal and technological changes on the future energy market. The key steps of the methodology for scenarios' building are: identification of key drivers, defining the alternative scenarios, checking the plausibility and consistency, narrative construction. After that an iterative process involving stakeholders and decision-makers is necessary to strengthen the scenarios, followed by testing the scenarios, and finally their use in the decision-making process. This process will be achieved by the exploitation of results and will be based on the transfer of the results to the potential beneficiaries such as the European and national decision-makers.

After an introduction briefly recalling the present status and historical development of nuclear power especially in the European Union, the second section is devoted to the methodological considerations for scenario building. A summarized presentation of Net Zero Emissions energy scenario is included to understand the elements describing the normative elements of the visions and policies. Some existing energy scenarios for the Europe Union development are also discussed.

The third section presents the approach used to handle the complexity resulting from the long-term perspective of the scenarios and the multitude of uncertainties, for example those related to evolutions in key parameters, and in technological and societal development. For the twelve established key influencing factors, the first simplification was to reduce to six the number of factors having a broad spectrum of variation. Six factors (decarbonization, grid modernization, interconnectivity, resilience and adaptation, global cooperation, and carbon capture) were considered with evolutions described by the current vision of the climate neutrality or those normative scenarios derived from net zero emissions. The broad variation of the other six factors (renewable energy, electrification, energy storage, energy efficiency, behavioral changes, and technological assessment) was considered and detailed in three scenarios (high, medium, and low).

By considering the most relevant cases of the variation of the previous key factors, a set of four scenarios for nuclear power development is developed and presented in the fourth section. The scenarios are: 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 to support accelerated implementation of renewables), and Nuclear Renaissance (nuclear accelerated by the new reactor technologies).

A discussion on the plausibility of these four scenarios is presented in the fifth section, followed by the construction of the narrative of each scenario. Further steps (an iterative testing process involving stakeholders) are mentioned, followed in the sixth section by the main conclusions for the whole work. References are provided in section 7.

1 Introduction: Status and short history of nuclear power in Europe

Currently, in the Europe Union, the nuclear power represents more than a quarter of the total electricity production [1] with operational reactors in 13 countries: Belgium, Bulgaria, Czechia, Germany, Spain, France, Hungary, the Netherlands, Romania, Slovenia, Slovakia, Finland, and Sweden [1]. Considering the EU rules, the decision to use nuclear power or not is the prerogative of the Member States. There are more than 100 nuclear reactors in operation [2] with installed power of around 100 GWe [3].

Nuclear power is an important contributor to the following EU energy objectives: (1) reduction of CO_2 emissions, (2) a viable and diverse energy mix, (3) ensuring security of supply and energy independence.

The largest share of nuclear electricity in the electricity mix is seen in France (68.9 %), followed by Slovakia (52.4 %) and Belgium (50.6 %) [1]. To be noted, currently over half of nuclear electricity in the EU is produced by France.

The history of nuclear electricity relates to the post-World War II energy needs, in the context of growing demand for reliable and abundant sources of energy to support reconstruction and economic growth. On the other hand, some crises, for example the oil crisis of the 1970s (triggered by factors like the 1973 Arab-Israeli War and the subsequent oil embargo imposed by OPEC) determined many countries to reduce their dependence on foreign sources of energy by diversifying their energy sources. As a result, there was a heightened awareness of the limitations of relying solely on fossil fuels, especially oil, for energy. Policymakers and energy planners began actively seeking alternative sources of energy that were domestically available and less subject to the volatility of international oil markets. For some of the countries, the implementation of ambitious nuclear power programmes was the appropriate solution.

Nuclear national programmes

The French government launched the "French Nuclear Energy Program" in the 1970s to reduce France's dependence on oil and increase energy security through the construction of a substantial number of pressurized water reactors (PWRs). As a result, France became heavily reliant on nuclear energy for electricity generation. West Germany pursued an extensive nuclear power program in the 1970s as part of its energy diversification efforts. Sweden began its nuclear program in the 1970s to reduce dependence on oil and address energy security. The U.S. government provided incentives and support for nuclear expansion, leading to a significant number of new nuclear power plant construction projects, to reduce the oil dependence. Japan, being highly dependent on oil imports, embarked on an ambitious nuclear energy program in the 1970s and 1980s. The government aimed to reduce its reliance on imported oil and diversify its energy mix by building a substantial number of nuclear reactors. South Korea initiated its nuclear program in the 1970s as well, motivated by energy security concerns and the need to support its growing economy. South Korea has since become one of the leading nations in terms of nuclear power capacity.

National nuclear programme, communist countries

For the Soviet Union and other communist countries, the stimulation of the nuclear peaceful development during the mid-20th century was triggered by the large amounts of electricity needed by the industrialization policies and economic development. Nuclear energy was seen to modernize and advance the nation's infrastructure. At the same time, the development of nuclear energy contributes to less vulnerability of the energy supply. It should be noted, by using an extensive centralized planning, the communist governments were interested in large energy capacities to control over the key industries (at least). In this context, the centralized nature of nuclear power was in synergy with the state ownership and planning.

Both in some western countries and some of the communist bloc, in the broader context of the Cold War, there was also an interest in nuclear development for the military purposes. Also, the scientific value of the nuclear achievement as a source of national pride was a factor to stimulate nuclear power development.

Beyond these elements, there are many other factors, for example energy efficiency, energy security, technological advancement, strategic positioning, environmental benefits, diversification of energy sources, all of them contributing to the support for nuclear power development globally or in a specific region or country.

The history of nuclear electricity was marked by important achievements. The most significant is the consistent contribution to the reliability of the baseload supply. This has been particularly important for ensuring grid stability and meeting the electricity demand of industrialized nations. Another important contribution is the low-carbon energy provided with minimal greenhouse gas emissions during electricity generation. This has contributed to efforts to combat climate change by reducing carbon dioxide emissions, making nuclear power a valuable tool in the transition to cleaner energy sources. Several emerging economies, such as China and India, have invested heavily in nuclear power to meet their growing energy demands while reducing their reliance on fossil fuels. This has contributed to the regional and global development.

During the time, many nuclear reactors have demonstrated the capability to operate for several decades, often surpassing their originally planned operational lifetimes. This longevity has allowed countries to maintain a stable source of electricity while amortizing the initial construction costs over a longer period. Significant advancements in reactor design, safety protocols, and regulatory oversight have been implemented. Modern nuclear reactors incorporate enhanced safety features to mitigate the risk of accidents. Progress has been made in managing and storing radioactive waste generated by nuclear power plants. Advanced technologies and secure disposal methods have been developed to handle and store nuclear waste more safely. International agreements and safeguards, such as the Treaty on the Non-Proliferation of nuclear weapons (NPT) and the International Atomic Energy Agency (IAEA), have been instrumental in preventing the proliferation of nuclear weapons while enabling the peaceful use of nuclear energy.

The historic evolution of nuclear energy has been greatly influenced by three events classified as severe accidents, at Three Mile Island (1979), Chernobyl (1986), and Fukushima Daiichi (2011).

These nuclear accidents raised public awareness about the potential risks of nuclear power and prompted governments and international organizations to reevaluate and strengthen nuclear safety measures. They continue to shape nuclear policies and public perception of nuclear energy worldwide.

TMI

The Three Mile Island (TMI) accident (the most serious accident in the history of the US commercial nuclear reactors) produced a partial meltdown of the core. Lessons learned from TMI led to enhanced safety protocols, improved training for operators, and stricter regulations for nuclear facilities. The TMI accident raised public concerns about the safety of nuclear power. It contributed to a slowdown in the construction of new nuclear reactors and to increased public scrutiny of the nuclear industry.

Chernobyl

The Chernobyl accident in Ukraine is considered the worst nuclear disaster in history. An explosion and fire at the Chernobyl Nuclear Power Plant's Reactor No. 4 released a massive amount of radioactive material into the environment. The explosion and initial radiation release resulted in the deaths of two plant workers, and 28 firefighters and plant personnel died from acute radiation sickness shortly after the accident. Thousands of people were exposed to high levels of radiation, leading to long-term health consequences, including an increased incidence of cancer and other radiation-related illnesses in the affected areas. A large exclusion zone was established around the Chernobyl plant, which remains off-limits for human habitation to this day. The city of Pripyat, which housed plant workers, remains abandoned. The Chernobyl disaster had global implications for nuclear safety, leading to changes in reactor design, safety regulations, and international cooperation to prevent similar accidents. The accident significantly damaged public confidence in nuclear energy, both in the affected region and worldwide. It became a symbol of the potential dangers of nuclear power.

Fukushima Daiichi

The Fukushima Daiichi nuclear disaster was triggered by a massive earthquake and tsunami in Japan. It resulted in the release of radioactive material from multiple reactor units at the Fukushima Daiichi Nuclear Power Plant. The Japanese government ordered the evacuation of tens of thousands of people from the affected area, resulting in a large and prolonged displacement of residents. Workers at the plant and emergency responders were exposed to elevated radiation levels during efforts to contain the crisis. However, there were no immediate fatalities directly caused by radiation exposure. The Fukushima disaster had a profound impact on Japan's nuclear policy. The country temporarily shut down its nuclear reactors, initiated comprehensive safety reviews, and revised its nuclear energy policy. Several reactors remained offline for an extended period, and Japan's reliance on nuclear power was reduced. The Fukushima disaster prompted a worldwide review of nuclear safety standards and emergency preparedness. It led to increased emphasis on safety assessments and upgrades at nuclear facilities, particularly those in seismically active regions.

In the last decades some countries decided to reduce their nuclear share in the electricity-mix or to phase-out completely. While motivations may vary by country, some common factors for the phase-out in some of EU countries include: (1) safety concerns resulted from the major nuclear accidents (Chernobyl, Fukushima Daiichi), (2) shifting of the public opinion (concerns about the safety of nuclear facilities, radioactive waste disposal, and the environmental impact of nuclear energy have led to anti-nuclear sentiment and influenced government policy), (3) environmental concerns (some EU countries decided to reduce greenhouse gas emissions based only on the increase of renewable energy sources as a better option to nuclear), (4) aging infrastructure (many nuclear power plants in Europe have reached or exceeded their originally planned operational lifetimes), (5) energy diversification (reducing the dependence on a single energy source, such as nuclear power), (6) economic factors (high costs of nuclear reactors, considering the entire life cycle), (7) technological alternatives (advances in renewable energy technologies, such as wind, solar, and energy storage, have made these sources more economically viable), (8) political shifts (changes in political leadership and government priorities).

On the other hand, some countries continue to invest in and operate nuclear reactors as part of their energy mix. The decision to invest in nuclear or to phase out nuclear reactors is a complex one, influenced by a combination of safety, environmental, economic, and political factors specific to each country.

Phase-out in Germany

Germany progressively phased out nuclear reactors ("Energiewende"), with a drop of 58.7% in nuclear share (2021 vs 2006) and the intention to close all nuclear power production in the next 3-5 years. The initial decision was produced in the post-Fukushima context. This decision marked a shift from the previous policy, which had extended the operating lives of some nuclear reactors. Germany's plan involves a phased shutdown of all nuclear reactors. The phase-out is part of Germany's broader transition to renewable energy sources, such as wind and solar power. The phase-out of nuclear power is coupled with efforts to improve energy efficiency and promote energy conservation to ensure a reliable energy supply. The phase-out also involves addressing the challenge of nuclear waste disposal. Germany has been working on developing safe long-term storage solutions for radioactive waste generated by nuclear reactors.

Poland commitment for nuclear

Poland decided to build a first nuclear power plant based on several key factors and considerations. The most important relate to the high dependence on coal for its electricity generation and to the energy security aspects. To enhance energy security and reduce vulnerability to fluctuations in coal prices and supply, the Polish government has sought to diversify its energy mix. Nuclear power is seen as a reliable and stable source of electricity that can help achieve this goal. Another factor relates to the growing economy requiring a consistent and ample supply of electricity. In the climate change context, Poland, like many other European countries, faces pressure to reduce its greenhouse gas emissions and transition to cleaner energy sources in line with international climate agreements. Nuclear power is considered a low-carbon energy source, and its development can help. Developing nuclear power provides Poland with greater energy independence, reducing its reliance on energy imports from neighboring countries and enhancing its self-sufficiency.

Despite this polarization, nuclear remains a crucial sector for energy production in the EU, offering powerful contribution for energy security, large contribution to the decarbonization goal, and creating a strong local supply chain with high-quality jobs. Nuclear electricity in EU is a major contributor to the decarbonization strategy, currently representing around 40% of the free-carbon electricity production [3].

A set of EU Member States keep nuclear in the national energy mix, based on the extension of the lifetime of the current fleet. Other countries intend both long-term operation (LTO) and the building of additional capacities. LTO is already decided or in advanced progress for some NPPs such as: Kozloduy (Bulgaria), Dukhovany and Temelin (Czech Republic), Krško (Croatia and Slovenia), Loviisa and Olkiluoto 1&2 (Finland), Paks (Hungary), Cernavoda U1 (Romania), Bohunice U3&4 (Slovakia), Borssele (Netherlands). In France, a large LTO project (grand carénage project) is in progress.

Some new nuclear power plants are planned to be built in some EU countries. On the other hand, the current policies of several MSs are considering nuclear plants as a feasible option to meet their growing energy needs, especially based on the deployment of small modular reactors (SMRs).

The most relevant cases are presented below [3]:

– Bulgaria: two new reactors at Kozloduy, together with the intention to re-start Belene project, including the consideration of SMR option,
– Czech Republic: Dukhovany U5&6, Temelin U3&4, also exploring SMR implementation,
– Estonia: intention to build first NPP by 2035, possible SMR technology,
– Finland: planning for SMRs both for electricity and cogeneration,
– France: construction up 14 new reactors by 2035, including SMRs,
– Hungary: project Paks II (2 new units to be operational in 2032),
– Netherlands: intention to build two new NPPs by 2035, exploring also SMR option,
– Poland: more units (a total capacity of 6 GWe), the first one to be commissioned in 2033,
– Romania: two new units Cernavoda U3&4 (operational in 2032) and first NPP based on SMR (commissioned by 2028),
– Slovakia: a new unit at Bohunice (operational in 2031),
– Slovenia: considering the building of a second NPP,
– Sweden: planning to replace old nuclear units with new ones, exploring also SMR option.

Also, it should be mentioned the tendency of nuclear development in UK, as former EU member, developing currently two French-made EPR2 reactors at Hinkley Point C.

The last group of countries (Germany, Italy, Lithuania, and Spain) are clearly oriented for the decommissioning of their nuclear reactors. A total number of 26 reactors are under decommissioning process in Germany, and 3 operating reactors planned to shut down in 2023. Spain is planning to reduce the nuclear installed capacity by 2030. In Belgium, the shutdown of Doel 1&2 old reactors was announced.

Other countries like Austria and Luxembourg have a strong anti-nuclear position. At the same time, nuclear is considered controversial in some countries such as Belgium, Portugal, Denmark.

The last evolutions at global and EU level, especially the energy crisis and the war in Ukraine, together with the increasing of the climatic pressures, creates more favorable conditions for nuclear development on short- and medium-term.

The current deliverable discusses the possible roles of nuclear power in the climate neutral context of the EU at the horizon of 2050. Based on the analysis of the current situation and of the projections of development for the future 3 decades, considering the possible evolutions produced by the disruptive technologies and other factors, a set of scenarios for nuclear power are defined and discussed.

2 Methodological considerations for energy scenario building

Energy scenarios are alternative views of the future energy development. The scenario method has been widely used in different areas such as the general development of economy or society, in business, technological evolutions, energy etc. It is considered as "an unrivalled technique to learn about the future before it happens" [4].

The scenarios may be used for an exploratory purpose, for example to identify the implications of different assumptions and understand possible pathways to build a future in accordance with expectations for innovation and changes. Other scenarios may be considered normative scenarios, being used to drive the world or a country/region towards some specific objectives. The case of net zero emissions (NZE) [5] scenario is considered more normative than exploratory. The exploratory scenarios may provide more neutral facts to decision makers, for example the scenarios Jazz and Symphony developed by World Energy Council (WEC) [6] to 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 is focused on environmental sustainability through internationally coordinated policies and practices.

The scenarios may be considered as experiments to simulate possible futures and are very useful for decision makers to have concrete visions on medium and long term. Scenario preparation involves significant efforts to understand the input data (such current situations, variables, constraints etc.) together with the associated uncertainties, whose implications are then considered in organized exercises.

The construction of the scenario, referred to as scenario building, is a strategic planning method based on the analysis and understanding of current situation, historical trends, and existing predictions/projections of the future.

A consistent description of the possible evolutions must be developed as pathways towards the future. The plausibility of these pathways transforms them into scenarios. An exploration of the associated uncertainties is necessary. Scenario building is a valuable tool also to support the management of risks, allowing organizations and individuals to reflect in more details and provides them with a structured approach to navigate the complexities of an uncertain future. Generally, the spectrum of possible situations is a broad one, from the most optimistic to the most pessimistic.

The scenario building is invaluable for strategic planning and risk management. It is not just a planning tool, it is a strategic mindset fostering resilience and innovation in the face of an ever-evolving world. When faced with complex and uncertain situations, scenario building provides decision-makers with a more informed basis for making choices. It helps them weigh the potential benefits and drawbacks of various actions under different circumstances.

By considering a variety of scenarios, one can uncover hidden risks and opportunities that might not be apparent when focusing solely on a single, linear projection of the future. This helps in identifying blind spots and vulnerabilities in existing strategies. Armed with insights from scenarios, decision-makers can fine-tune their strategies and plans to be more flexible and responsive. This agility is essential for adjusting course when circumstances change.

Scenarios foster dialogue and collaboration within organizations and across sectors. They provide a common language and framework for discussing the future, facilitating better communication and alignment among stakeholders. Scenario building encourages long-term thinking and the consideration of systemic trends. It helps organizations and individuals transcend short-termism and make decisions that are sustainable and resilient over time.

The scenarios developed by ECOSENS project are considered key outcomes and should be transferred to the potential beneficiaries identified in the frame of results exploitation process, for example to European and national decision-makers.

The key steps of the scenario building process are presented in Table 2.1, including the final step of the use of the scenarios.

Table 2.1 Key steps for the scenario building process

	Key step	**Description**
1	Identification of key drivers	identifying the relevant influencing factors (technological, social, economic, etc.) could significantly impact the future evolutions
2	Defining the alternative scenarios	developing a set of scenarios based on different combinations of the impacts of the relevant influencing factors, and considering logical extrapolations of current trends or plausible disruptions
3	Plausibility and consistency	check the internally consistency and plausibility of each scenario, including the extreme or unlikely situations,
4	Narrative construction	create detailed narratives, describing the possible futures, easily to be visualized and understand, with including information how the influencing factors shape the scenarios
5	Iterative process	an update of the scenarios will be done in case of any new available information or the changing of circumstances
6	Testing	understand how the strategic planning perform under each scenario trying to test the resilience of them across multiple future conditions.
7	Use	organizations and decision-makers explore the possible impacts of their strategies and plans in the context of different scenarios to identify vulnerabilities, opportunities or needs for change; the scenarios may provide decision-makers with a more comprehensive understanding of uncertainties and their potential impacts.

In previous ECOSENS work [7] the key influencing factors for the development of the energy sector were identified and discussed considering also the impact on the nuclear development. The definition of the scenarios will consider the different combinations of the impacts of the relevant influencing factors and will be presented in Section 4 of this report, together with their narratives, describing the possible futures.

In the following some considerations about the plausibility of the scenarios [8] will be introduced. The discussion of the plausibility of energy scenarios must consider the feasibility of the visions obtained by extrapolation the present situation, by using predictions and projections, together with the possible impacts of the influencing factors defined in the previous analysis [7].

The discussion of the plausibility of energy scenarios often begins with the technological feasibility, more exactly the availability and maturity of the considered technologies, for example answering the following question. *Are the technologies required for the scenario already in existence or in advanced stages of development?*

The second element in the discussion is the economic feasibility. The costs to transform the scenarios into reality involving specific energy sources or technologies should be competitive with the existing energy options, with the resources and expectations of the society. *Are the technologies and the proposed changes competitive considering the other existing solutions in the context of the existing constraints?*

Since the policies and regulations play a significant role in shaping the energy landscape the discussion of the scenario plausibility will consider the alignment of the proposed changes with current and future policy frameworks, for example assessing the likelihood of policy support or barriers to the scenario's implementation, such as subsidies, carbon pricing, or emissions targets.

The next step is to consider another aspect of the implementation context, that is the market. Each scenario should be assessed considering the market forces and dynamics, discussing the potential market disruptions. *Is there sufficient alignment between market needs (energy demands, rules, and constraints) and are the changes reflected in the scenarios? How might market trends and consumer preferences affect the scenario's plausibility?*

From the point of view of sustainability impact the plausibility analysis should answer questions such as: *Are the developed scenarios compatible with sustainability goals and environmental regulations? Are there potential negative externalities that need to be addressed?* The assessment should approach different impacts of the scenarios, such as potential job displacement and community concerns.

Another aspect is directly connected with the existing energy infrastructure and possible future evolutions. *Is the necessary infrastructure feasible to be built or modified to support the defined scenarios?* The discussion must consider the assessment of the resilience and reliability of the energy infrastructure versus the proposed changes, for example the challenges in grid integration and energy storage.

The cooperation at regional, country, or international level should be discussed to understand the plausibility of the changes in the context of the developed scenarios. *For example, could geopolitical factors and international agreements impact the plausibility of a scenario?*

Finally, the recognizing of always existing uncertainties associated with energy scenarios should introduce some sensitivity analyses to account for them.

One of the main suppositions for the scenario building for the current report is linked with the general context of the climate policies concretized in governmental and international measures/ strategies aimed at mitigating/adapting to the impacts of climate change. These policies are designed to address the growing concerns related to global warming, rising greenhouse gas emissions, and their associated environmental and socio-economic consequences.

According with [9] the urgency of climate measures is today a critical and pressing issue. Climate change is happening at an alarming rate, with increasingly severe and frequent extreme weather events, rising global temperatures, and the melting of polar ice. Many of the effects of climate change are irreversible over human timescales. Climate change is already causing significant harm to ecosystems, economies, and human health. It leads to more frequent and intense wildfires, floods, droughts, hurricanes, and heatwaves. Vulnerable communities, particularly in low-lying coastal regions and developing countries, are disproportionately affected. Climate change is a major driver of biodiversity loss, it threatens the existence of numerous plant and animal species. On the other hand, it has far-reaching social and economic implications, including displacement of populations, disruption of food and water supplies, and increased global conflicts. The financial costs of inaction on climate change are enormous. These costs include damage to infrastructure, reduced agricultural productivity, healthcare expenditures related to climate-induced health issues, and insurance payouts for climate-related disasters.

Failing to take swift action on climate change represents an intergenerational injustice, as it transfers the burden of addressing the problem to future generations. Inaction today will have profound consequences for the well-being and quality of life of our descendants. Climate change is a global issue that transcends borders. The impacts of climate change in one region can have cascading effects in others. For instance, melting ice in the Arctic affects sea levels worldwide, and the spread of infectious diseases can cross borders rapidly.

The window of opportunity to address climate change is rapidly closing. The Intergovernmental Panel on Climate Change (IPCC) and numerous scientific reports have emphasized the need for immediate and drastic emissions reductions to limit global warming to 1.5 degrees Celsius above pre-industrial levels. Beyond this threshold, the risks and consequences of climate change become significantly more severe.

Given the urgency of these factors, taking comprehensive and immediate climate measures is crucial. This involves reducing greenhouse gas emissions, transitioning to clean and sustainable energy sources, implementing climate adaptation strategies, and fostering international cooperation. The longer action is delayed, the more challenging and costly it becomes to mitigate the impacts of climate change and protect the well-being of both current and future generations.

In such conditions, in the current report the objective of climate neutral to be achieved around 2050 or later is considered as of major importance, agreed by a majority of countries, and yet feasible according with the last year evolutions. The supposition is the evolution of global world, and especially of the EU will follow the patterns described by the climate neutral vision.

Looking to the different positions, the commitments for climate neutrality in energy have some national particularities (in terms of the period to reach the neutrality, for example Germany (2045), most of the EU countries (2050) China (2060), India (2070), but there is a common direction for these commitments, even if the efforts are different.

For a better understanding, the Net Zero Emissions (NZE) energy scenario will be summarized below.

In 2021 the International Energy Agency (IEA) released a landmark report called the "A Roadmap for the Global Energy Sector” [10], revised in 2023 [11].

The NZE is a normative IEA scenario identifying the pathways to achieve net zero carbon emissions by 2050 in the energy sector. It meets key energy-related United Nations Sustainable Development Goals

(SDGs), in particular the "universal energy access" and "air quality" and is consistent with 1.5°C constraint.

A narrow but feasible pathway for the global energy sector limits the rise in global temperatures to 1.5°C above pre-industrial levels is described. The NZE is a crucial tool for policy makers, and also for the civil society, and economic sectors. The most important elements of the NZE are presented in Table 3.2.

According with NZE [10], total energy supply in 2050 "is close to the level in 2010, despite a global population that is nearly 3 billion people higher and a global economy that is over three-times larger".

The energy efficiency will be a major contributor to reduce the energy global consumption, a decrease of the annual rate of energy intensity of 4% to 2030 is supposed (about three-times the average rate achieved over the last two decades). The cut of the emissions is not limited to carbon dioxide, for example the methane emissions from fossil fuel supply will fall by 75% by 2030.

The renewables will rapidly increase reaching annual additions (for the first decade) of 630 GWe (PV, for Photo Voltaic) and 390 GWe (W, for Wind). According to NZE [10], for PV "this is equivalent to installing the world's current largest solar park roughly every day". In 2050 "almost 90% of electricity generation comes from renewable sources, with wind and solar PV together accounting for nearly 70%" [10]. In the NZE much of the remainder will come from nuclear power.

Table 2.2 Key elements of NZE scenario

	Key element	**Description**
1	Energy Transition	Rapidly shifting from fossil fuels to renewable energy sources (wind, solar, hydropower, biomass). It supposed a significant expansion of renewable capacity.
2	Electrification	The use of fossil fuel will be drastically eliminated by electrifying various sectors (e.g. transportation and heating).
3	Energy Efficiency	Large implementation of energy-efficient technologies and practices across energy, industrial, buildings, and transportation sectors.
4	Carbon Capture and Storage (CCS)	Deploying CCS technologies to capture and store emissions from industries that are hard to decarbonize (like heavy manufacturing and certain types of power generation).
5	Behavioral Changes	Encouraging changes in consumer behavior and lifestyle choices to reduce energy consumption and emissions.
6	Infrastructure Development	Investing in and upgrading infrastructure (smart grids, transmission lines, interconnectivity, charging) to support the transition to clean energy sources and electric vehicles.
7	Policy and Government Initiatives	Implementing strong policies, regulations, and incentives to drive emissions reductions and support the transition to clean energy.

The current pillars of low-carbon electricity (hydro and nuclear) will play an important role in ensuring the electricity during the transition period. The electrification will replace the energy based on the fossil fuels, especially in transportation and heating, for example in NZE an increasing of the electric vehicles to 60% of global car sales in 2030. In 2050, for the building sector more than 85% of buildings will be zero-carbon-ready. In 2050 electricity will represent almost 50% of the total energy consumption. According with [10] an increase of the electricity production of around 2.5 times of the today level is needed.

For the coal plants, "the least efficient coal plants are phased out by 2030, and the remaining coal plants still in use by 2040 are retrofitted" [10]. A sharp decline of fossil fuel will be produced, (the coal will reach in 2050 less than 1% in the total energy use, whereas the gas demand be reduced by 75%).

In terms of the emissions, the energy sector will by practically free-carbon, whereas "more than 90% of heavy industrial production is low-emissions" based on carbon capture and storage (CCS) and clean hydrogen, and "50% of heating demand met by heat pumps" [10].

An important effort in research, innovation, and development of new technologies is expected. For the first decade, the pathway may be followed by using technologies readily available today, but for 2050 the envisaged technologies are currently at the demonstration or prototype phase. According [10], "the biggest innovation opportunities concern advanced batteries, hydrogen electrolysers, and direct air capture and storage".

The level of changes and the involved speed to reach the objectives of NZE are based on a sustained support and participation of the stakeholders, including the general public. The NZE [10] estimates that "around 55% of the cumulative emissions reductions in the pathway are linked to consumer choices such as purchasing an EV, retrofitting a house with energy efficient technologies or installing a heat pump".

Since the current report is focused on the development of nuclear energy scenarios considering the EU context at the horizon of 2050 the following discussion will be framed on the EU existing scenarios in the energy field, with NZE as a general umbrella.

In [12] a comparative analysis of the EU energy scenarios is presented. Two groups of scenarios are considered, the first one (with 8 scenarios) is targeting a 50% reduction of GHGs (2030 vs 1990), the second one (16 scenarios) oriented to achieve climate neutrality by 2050, therefore similar with the ambitions of the roadmap for Europe becoming a climate-neutral continent by 2050 (European Green Deal [13] in line with the EU's commitment to global climate action under the Paris Agreement.

The European Green Deal (EGD) was released in December 2019 as a response to the environmental challenges and climate change urgency with the aim to support the transformation towards "a prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050" [13]. The carbon neutrality means net zero GHG emissions by the mid of century. The EGD takes into consideration the IPPC Special Report on 1.5 ^{0}C [14], and a set of studies performed under EC umbrella, complemented by some reports resulted from non-governmental institutes such as Oko Institute and Wuppertal Institute. These studies are predominantly based on energy scenario modelling, with including of some scenario analysis.

Three of the EC scenarios are presented in Table 2.3 based on the summarized description of [15].

Table 2.3 Some EC scenarios for energy

	Scenario	Summarized description
1	Energy Roadmap 2050	It is based on four technological developments: energy efficiency, renewable energy, nuclear energy and carbon capture and storage. Additionally, the role of consumers, investors, and regulatory frameworks are discussed. Five sub-scenarios are defined as: • High energy efficiency • High renewables • Delayed CCS and high nuclear • Low nuclear and high CCS • Diversified supply technologies
2	Clean Energy for all Europeans	It is based on the decarbonization pathway compatible with 2^{0}C with the targets agreed by EC in 2014. Four scenarios are defined as: (i)40% reduction of GHGs (vs 1990) until 2030 and 80-85% until 2050, (ii) emissions reduction from ETS sectors: 43% in 2030 and 90% in 2050 compared to 2005, (iii) non-ETS emissions reduction: 30% in 2030 (vs 2005), (iv) reduction of primary energy demand based on the energy efficiency by 27% -30% in 2030 (vs 2007).
3	A clean planet for all	It is a long-term vision to reach the climate neutrality "by investing into realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research - while ensuring social fairness for a just transition" [16]. Seven main strategic building blocks are used [16]: • maximise the benefits from energy efficiency including zero emission buildings, • maximise the deployment of renewables and the use of electricity to fully decarbonise Europe's energy supply, • embrace clean, safe and connected mobility, • a competitive EU industry and the circular economy as a key enabler to reduce greenhouse gas emissions, • develop an adequate smart network infrastructure and inter-connections, • gather the full benefits of bio-economy and create essential carbon sinks, • tackle remaining CO_2 emissions with carbon capture and storage.

Both the NZE scenarios (as global framing) and EU energy scenarios (as regional framing), presented above, are considered as staring point in the scenario building for nuclear power at the horizon of 2050 in the EU. The context will be refined treating the complexity of the key influencing factors identified in the previous ECOSENS work [7], together with the consideration of disruptive technologies development and deployment and the possible disruptions produced by a variety of crises [7].

3 Handling complexity

Considering the horizon of 2050, the transition towards a more sustainable, low-carbon, and renewable energy system is the central element of the published European energy scenarios [17], [12]. The transition is based on the following key elements:

(1) **decarbonization** (a massive shift away from fossil fuels such as coal, oil, and natural gas to free or low-carbon electricity),

(2) **renewable energy** (increasing share of solar, wind, hydro with tendency renewables will be dominant sources of energy generation,

(3) **electrification** (replacing traditional fossil fuel-based systems with electric alternatives, often powered by renewable sources, in various sectors such as transportation and heating),

(4) **energy storage** (development of the energy storage solutions, such as advanced batteries, to ensure a stable and reliable energy supply, in the context of a large penetration of the intermittent renewable sources),

(5) **energy efficiency** (developing and implementing technologies and practices that use energy more efficiently in industry, transportation, buildings and other sectors),

(6) **behavioral changes** (changing individual and societal behaviors related to energy consumption and production, for example the large spreading of the prosumers),

(7) **grid modernization** (decentralization of the grid to accommodate the intermittency of renewable, creating smart grids, capable of managing and distributing energy efficiently),

(8) **interconnectivity** (linking and harmonizing the electricity grids across countries and enabling the exchange of energy, enhancing the energy security and optimize the resource utilization, balancing supply and demand and contribute to market integration and to grid resilience),

(9) **resilience and adaptation** (resilience in the face of climate change impacts, ensuring that energy infrastructure can withstand and adapt to extreme weather events),

(10) **carbon capture and removal** (to offset emissions that are difficult to eliminate entirely, especially in sectors like heavy industry),

(11) **technological advancements** (significant advancements in clean energy technologies, energy storage, and carbon capture),

(12) **global cooperation** (increased international collaboration to achieve common climate goals based on international agreements like the Paris Agreement).

In the ECOSENS analysis [7] the main assumptions in terms of the evolutions of the demographics, GDP, quality of life, electrification, and decarbonization are discussed with the aim to describe the possible context to be considered for the development of the energy scenarios. More focused, the interest in ECOSENS project is to define possible energy scenarios based on renewables and nuclear, with a special focus on the new nuclear technologies. In this context, the SMR systems and Generation IV nuclear power plants will be approached.

It should be noted making projections of the energy demand on medium and long-term is highly challenging due to the uncertainties in the evolutions of the development (demographics, GDP, quality of life, energy intensity, level of electrification, etc.). On the other hand, the impact of disruptive technologies may introduce non-linear effects in the evolutions. An analysis of the possible impacts is presented in [7]. The possible evolutions of these technologies diversify the spectrum of the development scenarios and, implicitly, the set of future energy scenarios.

On the other hand, unexpected events such as the economic/financial crisis, pandemics, geopolitical conflicts and war, energy crisis and possible migration crisis may affect any projection on the energy demand [7] and can introduce more complexity in the set of scenarios.

In the following relevant scenarios for the possible evolutions of the following key factors are presented: electrification, energy storage, renewable energy, energy efficiency, behavioral changes, and disruptive technologies. For each of these six key factors three scenarios will be associated (High, Moderate, and Low) reflecting the level of influence mediated by the technological evolution, energy market penetration, and social adoption.

It should be noted the decarbonization is considered only in the High scenario based on the great determination at the EU level and the credibility of the success in reaching the objectives according with the planning. Also, the grid modernization and interconnectivity are only considered in the High scenario base on the cohesion policies aimed to reduce disparities and connect better the different countries and regions of the EU.

The assumptions for the scenarios for each of the key factors are presented in Table 3.1.

Table 3.1 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		

Resilience and adaptation are considered to be highly implemented, in accordance with the current policies. Similarly, global cooperation is considered to be credible at a high implementation level.

The carbon capture and storage key factor is credited at medium level implementation due to the modest progress observed today in the development and deployment of practical solutions.

A simplification of the complexity of the evolution landscape, resulted from the consideration of some evolution scenarios for the key influencing factors, was obtained by the reduction from 12 to 6 of the factors to be treated in three scenarios (High, Moderate, Low).

Even in this simplified situation, the number of the scenarios resulted from the combination of the different evolutions considered for the key influencing factor is large, 3^6=729. A further simplification is needed to reduce this complexity since in the usual practice of scenario only a few are retained to support a better vision of the decision-makers on the future.

In the following the scenarios for the six key factors considered with variable impact are discussed.

Electrification

One of the key elements of the assumptions for the energy sector is the doubling of the electricity needs called **electrification** (replacing traditional fossil fuel-based technologies with electric alternatives powered by low-carbon energy sources). Considering the level of electrification as a variable, a set of scenarios describing the possible evolutions for the level of the electrification variable may be elaborated.

For simplicity, three of them are presented in Table 3.2, considered as:

- High electrification scenario (H_El, a significant shift towards electricity as the primary energy carrier),
- Moderate electrification (M_El, moderate progress in transitioning to electricity),
- and Low electrification (L_El, limited progress in shifting from conventional fossil fuels to electricity for various energy applications).

The scenarios are considered at the horizon of 2050 in the EU.

Table 3.2 Selected scenarios for the level of electrification (EU, 2050)

	High (H_El)	**Moderate (M_El)**	**Low (L_El)**
Transportation	Majority of vehicles (cars, trucks, buses, and trains) will be electric. Battery electric vehicles (BEVs) and hydrogen fuel cell vehicles dominate the market. Public transportation systems will be fully electrified.	Electric vehicles are popular for personal use, but some sectors, like long-haul freight and aviation, still rely on advanced biofuels and hydrogen.	Internal combustion engine vehicles (ICEVs) remain the norm, with minimal adoption of electric vehicles. Biofuels may be the primary alternative to gasoline and diesel.

Buildings	Residential and commercial buildings will be equipped with electric heating and cooling systems. Most appliances, such as stoves and water heaters, are electric. Energy-efficient building designs and advanced insulation are common.	Heating and cooling systems in residential and commercial buildings are a mix of electric and high-efficiency natural gas systems. Appliance efficiency is improved.	Natural gas and oil heating systems are prevalent. Energy efficiency improvements are modest, and there is limited adoption of electric appliances.
Industry	Many industrial processes that previously relied on fossil fuels have switched to electric heating, powered by renewable energy sources. Electrification is also prominent in energy-intensive sectors like steel and cement production.	Some energy-intensive industries continue to use fossil fuels but employ carbon capture and storage (CCS) technologies to reduce emissions.	Fossil fuels continue to power most industrial processes. CCS technologies are not widely deployed.
Power Generation	The energy mix is dominated by renewable sources, including wind, solar, hydro, and geothermal power. Battery storage and other energy storage technologies are extensively used to manage the intermittent nature of renewables.	Renewable energy sources play a significant role, but natural gas-fired power plants with CCS are used as a backup during periods of high demand or low renewable generation.	
Benefits	Benefits of this scenario include significantly reduced greenhouse gas emissions, improved air quality, and reduced dependence on imported fossil fuels. However, it requires substantial investments in renewable energy infrastructure and grid upgrades.	This scenario balances emissions reduction with the need for energy security and affordability. It requires less immediate investment in renewable infrastructure but may face challenges in achieving long-term climate goals.	This scenario is characterized by slower progress in reducing greenhouse gas emissions, with potentially negative impacts on air quality and climate change mitigation efforts. It may also lead to increased energy security concerns due to continued reliance on fossil fuel imports.

The actual energy scenario for electrification in the EU 2050 will depend on policy decisions, technological developments, economic factors, and societal preferences in the coming decades. Transition to a high-electrification scenario is likely to be the most aligned with the EU's ambitious climate goals, but it will require concerted efforts and investments to make it a reality. The implementation is highly dependent on long term commitment (at EU, national, and regional level) and on some technological progress such as batteries, materials, local infrastructure.

Energy storage

Energy storage is crucial for balancing supply and demand, integrating intermittent renewable energy sources, and ensuring a reliable and resilient energy grid. To reduce the complexity of the discussion, three scenarios are defined as:

- High energy storage (H_ES, a widespread deployment of various energy storage technologies to enhance grid flexibility and reliability),
- Medium energy storage (M_ES, moderate energy storage deployment with a focus on providing reliability and backup),
- and Low energy storage (L_ES, energy storage is limited, and the energy system relies more heavily on conventional sources).

The discussion of the scenarios is presented in Table 3.3.

The implementation of the energy storage for the EU in 2050 will depend on policy decisions, technological advancements, economic factors, and public preferences. It must be noted the level of energy storage capacity will significantly impact the EU's ability to reduce greenhouse gas emissions, achieve energy independence, and ensure a reliable and resilient energy system.

Table 3.3 Selected scenarios for energy storage (EU, 2050)

	High (H_ES)	**Moderate (M_ES)**	**Low (L_ES)**
Energy mix	The energy mix consists predominantly of renewable sources such as wind, solar, hydro, and geothermal power. A significant portion of energy generation comes from intermittent sources like wind and solar.	The energy mix includes a substantial but not overwhelming share of renewables, with a mix of conventional and intermittent sources.	Conventional fossil fuels such as natural gas, coal, and oil continue to be a significant part of the energy mix, providing reliable baseload power. While there is some use of renewable energy sources, their intermittent nature is seen as a challenge rather than an opportunity, and their contribution to the grid is limited.

Large-Scale Batteries	Extensive use of large-scale battery storage systems helps smooth out fluctuations in renewable energy generation. These batteries store excess energy when supply exceeds demand and release it during periods of high demand or low renewable output.	Battery storage systems are deployed strategically, mainly to address short-term fluctuations in renewable energy generation and provide backup power during emergencies.	Energy storage technologies are sparingly deployed, mostly in niche applications, and not used extensively for grid balancing.
Pumped Hydro and compressed air Storage	The most hydro plant having water accumulation reservoirs in the mountain region will be modernized with the hydro pumping option. The investment in compressed air storage will be stimulated by the national programmes.	Existing and new pumped hydro storage facilities are utilized to store surplus electricity by pumping water to higher reservoirs when electricity is abundant and releasing it through turbines when demand is high.	Existing pumped hydro and compressed air energy storage facilities are maintained and used to a limited extent to provide seasonal or longer-term energy storage.
Hydrogen Storage	Hydrogen is produced at high scale, through electrolysis, during periods of excess electricity and stored for use in various sectors, including industry, transportation, and power generation. Both normal and high temperature electrolysis will be developed and deployed.	A moderate hydrogen production by electrolysis will be reached, limited by the moderate performance in economics,	The hydrogen production by electrolysis during the period with energy excess remains at a modest level, only some countries will great variability will use it for the balance of the grid.
Advanced Grid infrastructure and Management	Smart grids and advanced grid management systems enable real-time monitoring and control of energy flows, optimizing the use of stored energy.	Grid infrastructure is upgraded to accommodate variable renewable energy sources and provide better demand-side management.	Grid infrastructure remains relatively unchanged from current levels, with minimal investments in smart grid technologies.

	This scenario prioritizes decarbonization, grid stability, and reliability, but it requires significant investments in energy storage infrastructure and technology development.	This scenario strikes a balance between the integration of renewables and the need for energy security and affordability. It may involve fewer upfront costs but might not achieve the same level of emissions reduction as a high-storage scenario.	This scenario may have lower upfront costs and could be perceived as more energy-secure in the short term, but it is less aligned with long-term sustainability and decarbonization goals.

Renewable energy

In the context of net zero emission (NZE) European energy scenario, renewable energy sources (RES) play a central role, the vision on the medium and long term being centered on the achievement of a dominant share in the energy mix. However, the acceleration of the implementation for renewables is highly dependent on various factors such as industrial capabilities to ensure a fast pace of new projects, technological advancements, economic considerations, and public preferences.

Achieving a high share of renewables in the energy mix is essential for the EU to meet its climate goals, reduce greenhouse gas emissions, and transition to a sustainable and low-carbon energy system. In order to introduce this variability into the discussion three scenarios are formulated as:

- High renewable share (H_Rs, achieve a high share of renewables in the energy mix by 2050, in line with ambitious climate goals and characterized by reduced greenhouse gas emissions, energy independence, and a significant reduction in fossil fuel us),
- Moderate renewable share (M_Rs, incorporating renewables while maintaining a balanced mix of diverse energy sources),
- and Low renewable share (L_Rs, EU relies more heavily on conventional energy sources and has a lower share of renewables in the energy mix with a prioritization of short-term energy security and affordability).

The discussion of the three scenarios is presented in Table3.4. The renewable energy scenarios are derived from the vision of EU establishing ambitious targets for renewable energy deployment. The primary target was to achieve at least 32% of the EU's total final energy consumption from renewable sources by 2030, and climate neutrality by 2050 based on a significant increase in the use of renewable energy sources. To reach this target the EU will stimulate investment in renewable energy technologies, including wind, solar, hydropower, and bioenergy. This involved both public and private sector investments to support the development and deployment of renewable energy projects. However, the implementation of this vision is strongly dependent on the future evolution of the energy markets, technological development, and public support. The three scenarios are aimed to describe this variability, despite the firm orientation of the EU policies in the energy decarbonization.

Table 3.4 Selected scenarios for renewable energy (EU, 2050)

	High (H_Rs)	Moderate (M_Rs)	Low (L_Rs)
Energy mix	The energy mix is dominated by renewable sources such as wind, solar, hydro, and geothermal power. Renewables account for more than 80% of electricity generation.	Renewables play a significant role, contributing around 50-60% of electricity generation. Solar and wind power are particularly prominent. Natural gas and nuclear power continue to provide baseload electricity and serve as a backup during periods of low renewable generation.	Conventional fossil fuels like natural gas and coal continue to play a significant role in electricity generation, providing baseload power. Renewables contribute a relatively small share of electricity generation, around 20-30%. Nuclear power remains an essential part of the energy mix, providing reliable, low-emission electricity.
Decentralization	A significant portion of renewable energy generation is distributed, with many small-scale solar panels, wind turbines, and local energy projects. Communities and individuals actively participate in energy production. The energy production system benefits from a large participation of the prosumers.	The classical centralized production and distribution of energy remains at a dominant level, the development of the smart grid will be moderate and linked with the new investment project in energy. The participation of the prosumers is considered moderate due to the evolution of economics.	The development of the distributed production and smart grids will be modest, associated with some special cases where the economics is very attractive.
Energy Storage	Extensive energy storage systems, including advanced batteries, pumped hydro storage, and hydrogen storage are deployed to manage intermittent renewable energy sources effectively.	The deployment of energy storage systems is moderate due to the insufficient performance in economics, and lack of success in the mitigation of environmental difficulties.	The deployment of energy storage systems is modest since the lack of success in innovative solutions to reduce the existing drawbacks.
Electrification	Electrification efforts are substantial, with most sectors, including transportation, heating, and industrial processes, transitioning to electric technologies powered by renewables.	Electrification efforts are selective, focusing on sectors where it makes the most economic and environmental sense, such as transportation and heating.	Electrification efforts are limited, and other fuels (e.g., natural gas, liquid fuels) continue to be used for transportation and heating.

Green Hydrogen	Hydrogen production through electrolysis using renewable electricity is widespread and used in various sectors, including industry and transportation	Hydrogen production through electrolysis using renewable electricity is moderately deployed due to the market conditions.	Hydrogen production through electrolysis using renewable electricity is limited to some countries where the variability induced by renewable is high and no hydro-pumping is feasible.

Energy efficiency

The energy efficiency is a key influencing factor in terms of reducing the energy wasting and to temperate the consumption of energy. The energy efficiency is approached at the generation, transport, and consumer's level.

Three scenarios were defined to describe the possible variations in the energy efficiency as:

- High energy efficiency (H_Eef, a strong emphasis on energy efficiency across all sectors of the economy),
- Medium energy efficiency (M_Eef, a moderate level of improving energy efficiency throughout the EU),
- and Low energy efficiency (L_Eef, the energy intensity remains relatively high).

A more detailed description of the scenarios is presented in Table 3.5.

The EU's energy efficiency implementation in the context of 2050 was driven by the broader objectives of reducing carbon emissions, combating climate change, and transitioning to a sustainable, low-carbon economy. As a starting point of the energy efficiency implementation, the EU has introduced the Energy Efficiency Directive, which set out binding measures to help member states use energy more efficiently. The directive covered various sectors, including buildings, industry, and transportation. It aimed to promote energy-saving practices and technologies.

However, achieving this goal will require coordinated efforts across the EU and significant investments in energy efficiency measures and technologies. The defined scenarios try to cover the possible variations in success of the implementation of the energy efficiency measures.

Table 3.5 Selected scenarios for energy efficiency (EU, 2050)

	High (H_Eef)	Moderate (M_Eef)	Low (L_Eef)
Energy Demand	Energy intensity is greatly improved, leading to substantial reductions in energy consumption per unit of economic output.	Energy demand per unit of economic output is lower than in the low-efficiency scenario, but there is still room for improvement in various sectors.	Energy demand in this scenario is likely to be driven by less efficient technologies and processes across various sectors, such as industry, transportation, and buildings.
Share of Renewables	Renewable energy sources are likely to dominate the energy mix, as energy efficiency measures help maximize their impact and reduce the overall energy demand.	The medium-efficiency scenario likely involves a significant increase in the use of renewable energy sources, alongside energy efficiency measures, to reduce carbon emissions.	Renewable energy sources may have a smaller share in the energy mix, as the focus is less on reducing energy consumption and carbon emissions.
Decarbonization	The high-efficiency scenario is closely aligned with the EU's decarbonization goals. Carbon emissions are substantially reduced due to lower energy consumption and a shift to cleaner energy sources.	The EU makes progress in decarbonizing its energy system, partly due to the adoption of more energy-efficient technologies and practices.	The low emphasis on energy efficiency could result in higher carbon emissions, as energy consumption remains high and is largely met by fossil fuels.
Circular Economy Practices	Highly prioritization of circular economy principles to reduce waste and maximize resource efficiency, further contributing to energy savings.	Circular economy considered important by many EU Member States, but not highly prioritized at EU level	Circular economy principle is approached case by case by each MS
Advanced Technologies	The high-efficiency scenario involves widespread adoption of advanced technologies, such as smart grids, energy-efficient buildings, electric vehicles, and industrial processes with minimal energy waste.	Moderate adoption of advanced technologies at the level of EU	Limited adoption of advanced technologies

Behavioral changes

Behavioral changes play a crucial role in the decarbonization of energy in the European Union (EU) by 2050. Achieving the EU's ambitious decarbonization goals relies not only on technological advancements and policy measures but also on changes in the way individuals, communities, and organizations consume and interact with energy.

The following scenarios were developed to describe the possible variation in the evolution of the behavioral changes:

- H_C (High Consumer Engagement Scenario, consumers are actively involved in shaping a sustainable energy future),
- M_C (Medium Consumer Engagement Scenario, consumers become more conscious of their energy choices and begin to make some efforts toward sustainability),
- And L_C (Low Consumer Engagement Scenario, consumers exhibit limited interest or motivation in changing their energy-related behaviors and choices).

The consumers' behavior and preferences can significantly influence the energy consumption and energy landscape. At the same time, the evolutions of the behavioral changes may be influenced by evolving policies and trends at the global/regional level.

A more detailed description of the scenarios is presented in Table 3.6.

Table 3.6 Selected scenarios for behavioral changes (EU, 2050)

	High (H_C)	**Moderate (M_C)**	**Low (L_C)**
Energy Consumption	Consumers prioritize energy efficiency, leading to substantial reductions in energy use per capita.	Consumers start to adopt more energy-efficient technologies and practices, resulting in lower energy consumption per capita	Consumers continue to use energy-intensive appliances and technologies without much consideration for energy efficiency
Investments in Energy- Efficient Products	Energy-efficient appliances, electric vehicles, and building retrofits are the norm, and consumers seek out the most efficient options available.	Energy-efficient appliances, electric vehicles, and home insulation become more common as consumers recognize the benefits of reduced energy bills and environmental impact.	Consumers may not prioritize energy-efficient appliances, insulation, or transportation options when making purchasing decisions.

Demand Response participation	Consumers actively engage in demand response programs and contribute to grid flexibility by adjusting their energy use patterns based on real-time data and incentives.	Consumers are more likely to participate in demand response programs, allowing for more efficient energy use during peak periods	Consumers are less likely to participate in demand response programs or smart grid initiatives, which could lead to less flexible and efficient energy use.
Adoption of Renewable Energy	Consumers invest in renewable energy systems for their homes and actively support clean energy initiatives.	Consumers show greater awareness of and interest in renewable energy sources, such as solar panels and wind turbines.	There is limited interest in or awareness of renewable energy sources among consumers, who predominantly rely on traditional fossil fuels for energy.
Sustainable Lifestyle Choices	Consumers may embrace sustainable living practices, such as minimalism, recycling, and reduced meat consumption, further reducing their energy footprint.	The changes of the behaviors towards more sustainability for the energy use are moderate, the consumerism will remain the main driver of the society.	Consumers will generally keep the present habits, the determination to produce major changes in energy consumption is low, new consumptions will appear due to the dominance of the consumerism, and generally, the impact in saving energy is low.
Consumer-Driven Innovation	Consumer demand for sustainable products and services drives innovation in the energy sector is high, leading to the development of new, efficient technologies and business models.	There is a moderate interest of consumers to stimulate innovation in the energy sector.	The consumers are low interested in the stimulation of innovation in relation with the energy savings.

The EU's energy scenarios in 2050 will be influenced by the degree to which consumers actively participate in energy conservation and renewable energy adoption. Policymakers and stakeholders play a crucial role in shaping these scenarios through initiatives that encourage and enable consumers to make sustainable choices.

Disruptive technologies

Disruptive technologies have the potential to fundamentally reshape the energy landscape, making it more sustainable, efficient, and responsive to the challenges of climate change, but also creating new style of consumption. Technologies like advanced renewable energy systems, energy storage, and carbon capture and utilization play a vital role in reducing greenhouse gas emissions to achieve carbon neutrality by 2050 in the EU.

Disruptive technologies enable the decentralization of energy production and distribution. Small-scale renewable energy systems, microgrids, and peer-to-peer energy trading platforms empower consumers to generate, store, and share energy locally, reducing reliance on centralized fossil fuel-based power plants.

Data-driven technologies, including artificial intelligence and machine learning algorithms, are instrumental in optimizing energy systems. They enable predictive maintenance, energy management, and grid operation, leading to reduced energy waste and cost savings. However, at least in the initial phase of the learning process, the processing of large amount of data to find an optimal solution will generate additional relevant electricity consumption.

Innovations in materials science and advanced manufacturing techniques can lead to more efficient and durable renewable energy technologies, such as solar panels and wind turbines. These advancements drive down costs and improve overall performance.

The widespread adoption of electric vehicles can significantly reduce carbon emissions from the transportation sector, and will reinforce the shift from primary energy to electricity. EVs, coupled with advancements in battery technology and charging infrastructure, play a pivotal role in achieving sustainable mobility.

Advanced energy storage technologies, including high-capacity batteries and innovative storage methods, are essential for mitigating the intermittency of renewable energy sources. They enhance grid stability and provide reliable backup power.

Hydrogen is a versatile energy carrier that can be produced from renewable sources and used for various applications, including fuel cells and industrial processes. Disruptive technologies in hydrogen production, storage, and transportation can contribute to a cleaner energy future.

Disruptive technologies in carbon capture and utilization can help remove excess carbon dioxide from the atmosphere, contributing to carbon neutrality and the fight against climate change.

The intelligent use of resources through digital technologies, automation, and AI can optimize energy production, distribution, and consumption, resulting in significant energy and cost savings.

The following scenarios were developed to describe the possible variation in the impact of the disruptive technologies on the energy sector:

- High impact of disruptive technologies (H_Dt, transformative technologies drive substantial changes in the energy sector),
- Moderate impact of disruptive technologies (M_Dt, moderate progress in the development and adoption of disruptive technologies in the energy sector),
- and Low impact of disruptive technologies (L_Dt, limited progress in the development and adoption of transformative technologies in the energy sector).

In the H_Dt scenario, the EU has embraced and fully leveraged disruptive technologies, leading to a highly efficient, sustainable, and resilient energy sector. Decarbonization goals are met well ahead of schedule, and energy systems are cost-effective.

The M_Dt scenario represents a more gradual transition, with some regions and sectors benefiting from disruptive technologies while others lag behind. Decarbonization progress is moderate, and cost considerations play a significant role.

The L_Dt scenario reflects minimal adoption of disruptive technologies, resulting in limited progress in decarbonization and energy efficiency. Traditional energy systems and practices persist, posing challenges in achieving environmental and energy security goals.

A more detailed description of the scenarios is presented in Table 3.7.

Table 3.7 Selected scenarios for disruptive technologies (EU, 2050)

	High (H_Dt)	**Moderate (M_Dt)**	**Low (L_Dt)**
Advanced Energy Storage	Highly efficient and scalable energy storage solutions, such as next-generation batteries and power-to-gas technologies, enable reliable energy supply from intermittent sources.	The development and implementation of efficient and scalable energy storage solutions (batteries, hydrogen) will be at a moderate level.	The deployment of the energy storage solutions will remain marginal (covering only few percent from the need).
AI, IoT, and Big Data Optimization	AI and IoT are fully integrated into energy systems, enabling real-time monitoring, optimization, and predictive maintenance. Big data analytics provide insights for efficient grid management, demand response, and consumer behavior analysis.	While AI, IoT, and big data are integrated into the energy sector, their implementation varies by region and sector. Some areas benefit from advanced grid management and energy optimization, while others lag behind.	The integration of AI, IoT, and big data is minimal. Traditional methods of grid management and energy production remain prevalent.
Advanced Robots and Material Science	Advanced robots and material science innovations have transformed energy infrastructure construction and maintenance. Maintenance and repair of energy facilities are mostly automated, minimizing downtime and improving efficiency.	Advanced robotics and material science innovations have improved energy infrastructure construction and maintenance, but their full potential is not realized due to cost constraints.	The adoption of advanced robots and material science innovations is slow due to cost considerations, leading to a reliance on conventional construction and maintenance practices.

Additive Manufacturing	Additive manufacturing will be largely adopted at global level, allowing an easily production process near the final customers.	Additive manufacturing is not reaching its potential due to the low deployment in condition of the needs to replace the old machineries and supply chain.	Additive manufacturing is used only in some special cases by a small number of companies.
Biotechnologies and Geoengineering	Biotechnologies have been harnessed for biofuel production and carbon capture, while geoengineering techniques help enhance the efficiency of renewable energy generation. Carbon sequestration methods have contributed to significant reductions in greenhouse gas emissions.	Biotechnologies play a role in sustainable biofuel production, but carbon capture and geoengineering methods are still emerging technologies.	Biotechnologies and geoengineering are niche and have not gained mainstream acceptance in the energy sector.
Drones and Blockchain for Grid Resilience	Drones are widely used for inspection and maintenance of energy infrastructure, making it easier to detect issues and carry out repairs. Blockchain technology secures energy transactions and enables decentralized energy trading.	Drones are used for inspection and maintenance in certain areas, while blockchain technology is employed in energy transactions but is not yet pervasive.	The use of drones and blockchain technology is limited, and decentralized energy trading has not gained traction.

4 Definition of the nuclear power scenarios

Considering the context of the climate neutrality in the EU with the current orientations targeting the electrification, energy efficiency and increase the renewables' share in the electricity production, four plausible scenarios for the evolution of the nuclear power are defined and presented in Table 4.1: Status Quo (NSQ), Nuclear Phase-Out (NPO), Nuclear and Renewables Synergy (NRS), and Nuclear Renaissance (NR).

For NPO, NRS, and NR, three sub-scenarios are defined (Table 4.1).

Table 4.1 Scenarios and sub-scenarios for nuclear power, on medium and long-term

Scenario	Description	Sub-scenario
Nuclear Status Quo (NSQ)	nuclear keep the own pace of development, not much influenced by RES (renewable energy sources) acceleration, but driven by energy security, economics and diversification of energy sources	-
Nuclear Phase-Out (NPO)	phase out progressively, LTO of existing plants or not in some national circumstances, implementation of advanced planned new investment (NPP having already the investment commitment), no new nuclear project	(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)
Nuclear and Renewables Synergy (NRS)	nuclear to support accelerated implementation of renewables (security of energy, backup, balance)	(NRS1) The mix will be dominated by RES, followed by Nuclear (base load mode needs), 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
Nuclear	nuclear accelerated by the new	(NR1) Accelerated development of nuclear

Renaissance (NR)	technologies (SMR and GIV)	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 the following some details for the scenarios and sub-scenarios are presented.

4.1 Status quo scenario

This scenario considers the nuclear will remain an option for the electricity for the current nuclear group of member states of UE. The nuclear sector keeps the own pace of development, not much influenced by the accelerated process of implementing RES (renewable energy sources - especially PV and W). 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. In this scenario, nuclear energy continues to be a part of the EU's energy mix, but there is little appetite for building new nuclear power plants. Certainly, some countries will decrease their nuclear share, but others will build new nuclear projects, leading to a similar share as the current one of nuclear in the total electricity.

Member states continue to operate and upgrade their current nuclear plants, but there is little appetite for the construction of new facilities. Nuclear energy remains a reliable source of low-carbon baseload power, but it does not play a central role in achieving ambitious carbon reduction targets. The EU focuses more on renewables and energy efficiency measures to meet its climate goals.

In terms of the variables discussed in the previous section, the NSQ scenario will be accompanied by the values from Table 4.1.1. These values are embedded in the specific scenario of each variable.

Table 4.1.1 Influencing factors values for NSQ scenario

	Variable	**Scenario**
1	Electrification	Medium
2	Energy storage	Low
3	Renewable energy	Low or Medium
4	Energy efficiency	Low or Medium
5	Behavioral changes	Low
6	Disruptive technologies	Low or Medium
7	Crisis	Low

In the NSQ scenario, the EU's member states continue to operate and maintain their current nuclear power plants. These existing facilities, which have been in operation for several decades, continue to provide a significant portion of the EU's electricity generation. It is possible a phase out in few nuclear countries, already engaged in such process. The closed nuclear capacities will be compensated at EU level by new nuclear investment, especially in the CEEC region.

Long-Term Operation (LTO) will be used for the most of NPPs to extend the operational lifetime beyond their originally designed operational period, typically from 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. Perceptions of the safety of nuclear power plants play a significant role in public acceptance or opposition to LTO. The public acceptance for nuclear LTO in the EU varies from country to country. Many people recognize nuclear power as a low-carbon energy source, which can contribute to climate change mitigation. Proponents of LTO argue that extending the life of existing plants can help reduce greenhouse gas emissions. The proximity of nuclear plants to communities, local employment, and regional energy needs can also impact public acceptance. Communities and regions with strong ties to nuclear power generation may be more supportive of LTO.

After 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. The societal view on nuclear dismantling and decommissioning is shaped by a combination of safety, economic, environmental, and community factors. Public engagement, clear communication, and effective regulatory oversight are essential in addressing these concerns and gaining public acceptance for decommissioning activities. The primary concern of the public is the safety of nuclear dismantling and decommissioning activities. There is a strong emphasis on ensuring that these processes do not pose risks to the environment, nearby communities, or workers involved in the cleanup. Transparency in the decommissioning process and trust in regulatory oversight are crucial. The public often demands clear, honest communication and regulatory assurance that risks are being effectively managed. In terms of the costs, many people are concerned about the financial aspects of decommissioning. They want assurance that the costs will not burden taxpayers and that the process will not result in economic disadvantages for local communities. The impact of decommissioning on local communities, including employment opportunities and the local economy, is important. Communities may be supportive if they see benefits in terms of job creation or land redevelopment.

In NSQ scenario the EU continues to pursue its emissions reduction targets, although 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. From the point of view of the energy mix, while nuclear energy remains a stable and reliable source of electricity, the EU member states 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 economic feasibility of the NSQ scenario depends on factors like 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. Important 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 is less reliant on energy imports compared to scenarios where nuclear energy is phased out.

In terms of RDI, in NSQ scenario the research and innovation will be primarily focused on safety improvements, operational efficiency, and waste management rather than significant expansion.

4.2 Nuclear phase-out scenario

The NPO (Nuclear phase-out) scenario is described by a gradually phase out of the NPP considering a LTO process limited to some of the existing plants and restricting the nuclear investment to the advanced planned project (NPP already having the investment firm commitment).

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

In terms of the variables discussed in the previous section, the NPO scenario will be accompanied by the values from Table 4.2.1. These values are embedded in the specific evolution scenario of each variable.

Table 4.2.1 Influencing factors values for NPO scenario

	Variable	**Scenario**
1	Electrification	Low or Medium
2	Energy storage	High
3	Renewable energy	High
4	Energy efficiency	High
5	Behavioral changes	High
6	Disruptive technologies	High
7	Crisis	Low

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 lifespans or sooner, and no new nuclear plants 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 shutdown process of nuclear reactors 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 continuously monitor 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 affordability and reliability of the alternative energy sources. In NPO scenario the achievement in the implementation of renewables has to be at the High level in order to ensure the necessary installed capacity taking into consideration the effect of the usual intermittency in electricity generation. Such development introduces important costs for grid integration in order to ensure a stable energy 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 the 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 the Moderate level 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 (EU) 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)

4.3 Nuclear and renewable synergy scenario

The NRS (Nuclear and Renewables Synergy) scenario is characterized by nuclear development to support accelerated implementation of renewables 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 renewable energy sources to achieve its climate goals. Member states invest in maintaining their current nuclear power capacity while also expanding renewable energy infrastructure. Renewable energy sources (RES), such as solar or wind, generate electricity when conditions are favorable (i.e., on sunny or windy days), while nuclear power provides a consistent baseload supply to fill in gaps when renewable output is low.

Nuclear power will continue to play a significant role in the EU's energy mix. Existing nuclear power plants will be well-maintained and operated safely. Member states may also invest in the construction of next-generation nuclear reactors, such as small modular reactors (SMRs) and advanced fast breeder 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 renewable energy, the EU experiences substantial growth, particularly wind and solar power. Member states continue to invest heavily in renewable energy 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.

In terms of the variables discussed in Section 3, the NRS scenario will be accompanied by the values presented in Table 4.3.1. These values are embedded in the specific evolution scenario of each variable.

Table 4.3.1 Influencing factors values for NRS scenario

	Variable	Scenario
1	Electrification	High
2	Energy storage	Medium
3	Renewable energy	High
4	Energy efficiency	High
5	Behavioral changes	Medium
6	Disruptive technologies	Medium
7	Crisis	Low

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 needs), 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 (to supply peak load/baseload plants). 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 "poisoning" phenomena), 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 development and implementation of the energy storage.

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 power plants. There are various methods for thermal energy storage in the context of nuclear power:

(1) molten salt storage (a mixture of salts, typically a eutectic mixture of lithium, sodium, and potassium salts is used to retain the heat for extended periods, and it can be transferred to a heat exchanger when needed to produce steam and generate electricity)

(2) concrete storage (use massive blocks of concrete to store the heat in excess); method is less efficient than molten salt but can be cost-effective

(3) bedrock storage (use rocks or sands to store the heat)

(4) high-temperature steam accumulators (devices storing high-temperature, high-pressure steam generated by the nuclear reactor during periods of low electricity demand, the steam is later released to drive turbines and produce electricity when demand increases)

(5) phase change materials (substances that absorb and release heat during phase transitions, such as melting or freezing, excess heat is used to melt the material, and the stored thermal energy is released when the material solidifies)

(6) underground thermal storage (utilize underground reservoirs or geological formations to store excess heat; hot water or steam generated by the reactor is injected into the reservoir during low-demand periods and later withdrawn to generate electricity).

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 intermittent renewables 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:

(1) energy density (high-energy-density batteries are essential for grid-scale energy storage).

(2) environmental impact (battery production, including mining, extraction, use rare minerals, and disposal has a significant environment impact; more sustainable battery technologies and recycling methods has to be developed in the near future).

(3) cycle life and durability (the limited number of charge and discharge cycles before their capacity degrades introduce the urgent need for improvement)

(4) safety (thermal runaway and the risk of fires or explosions, continue to be a significant issue and needs future research, innovation and developments)

(5) charging time (still not as fast as refueling with fossil fuels. Reducing charging times for electric vehicles and grid-scale batteries can enhance their convenience and usability.

(6) circular economy (recycling and disposal of batteries is a growing concern, given the increasing number of batteries in use)

(7) resource availability (most of batteries rely on lithium, cobalt, and nickel, with supply chain limitations and environmental concerns)

(8) grid integration (integrating large-scale battery storage into the electrical grid is complex requires advanced control systems, grid infrastructure upgrades, and regulatory changes)

(9) cost (cost of battery production, including materials, manufacturing processes, and recycling, remains a challenge)

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.

Electrolysis is a widely used method to produce hydrogen from water. It involves the splitting of water molecules into hydrogen and oxygen using an electrical current. Proton Exchange Membrane (PEM) electrolysis and Alkaline electrolysis are two main technologies used for grid-scale hydrogen production.

Electrolysis can be powered by surplus electricity from renewable sources like wind and solar when the grid has excess capacity. Electrolysis may be easily supported by renewable hydrogen production (solar/wind/hydro to hydrogen) and by nuclear (nuclear hydrogen production). The high temperature electrolysis (HTE) may be used in case of nuclear by using reactors with high operational temperature.

Currently only 1% of the total hydrogen is produced by electrolysis. The dominantly process is the conventional method (Steam Methane Reforming) used in industry for ammonia production, based on the reaction of natural gas with steam to produce hydrogen and carbon dioxide. This method is an important contributor to carbon emissions at global level (around 3%) and need CCS (carbon capture and storage) to reduce environmental impact

The production of green hydrogen is very useful for industrial decarbonization (ammonia, cement, steel production, to develop zero emissions transportation (replace fossil fuels by fuel cell electric vehicles), to be injected into de natural gas pipes (P2G, Power to Gas) to reduce the carbon footprint of natural gas for heating and power generation, or to produce synthetic fuels by combining CO_2 (managed by CCS) and hydrogen.

In another option, hydrogen is used as an energy carrier to store excess energy and then converted it back into electricity when demand is high, thus providing a stable and continuous power supply. Also, hydrogen may be used as an energy export approach in regions with abundant renewable energy resources.

Considering the NRS scenario, due to the significant development of nuclear to cope with RES variable production, in some configurations waste heat from nuclear power plants 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 renewable 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 NRS 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 economic feasibility of this scenario is supported by the combination of stable, long-term baseload power from nuclear energy and the decreasing costs of renewable energy technologies. Energy markets are structured to incentivize the use of low-carbon technologies, ensuring a sustainable and affordable energy supply for EU citizens and industries.

4.4 Nuclear renaissance 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 GIV)

In this scenario, the EU experiences a renewed interest in nuclear energy. Member states invest in the construction of new nuclear power plants, 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 small modular reactors (SMRs) and Gen IV 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 terms of the variables discussed in Section 3, the NRS scenario will be accompanied by the values presented in Table 4.4.1. These values are embedded in the specific evolution scenario of each variable.

Table 4.4.1 Influencing factors values for NR scenario

	Variable	Scenario
1	Electrification	High
2	Energy storage	Low
3	Renewable energy	Medium or Low
4	Energy efficiency	Medium
5	Behavioral changes	Medium or Low
6	Disruptive technologies	Medium
7	Crisis	Low

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 Low 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 development of the renewables 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.

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

The development of the new system 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 volume of nuclear waste, 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 the variability of wind and solar energy, ensuring a reliable and resilient energy supply.

In terms of the nuclear safety and public acceptance, strict regulatory measures are put in place 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.

5 Considerations on the nuclear development scenarios

A detailed view for the nuclear power development at the horizon of 2050 is presented in [18] as a coordinated work based on the perspectives on the national nuclear programs at the level of member states. Therefore, the document is an integration of the national views on the future of nuclear power. The document is annually updated, reflecting the last evolutions in the national policies, strategies, and programs.

The data are aggregated at regional and global level. Unfortunately, the data for EU are not directly represented. In [18] the Europe is represented by two regions, based on UNO grouping: (1) North, West, and South countries, (North: Denmark, Estonia, Faroe Islands, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, UK; South: Albania, Andorra, Bosnia, Croatia, Greece, Italy, Malta, Montenegro, North Macedonia, Portugal, San Marino, Serbia, Slovenia, Spain; West: Austria, Belgium, France, Germany, Liechtenstein, Luxembourg, Monaco, Netherlands, Switzerland) (2) East European Countries (Belarus, Bulgaria, Czech Republic, Hungary, Moldova, Poland, Romania, Slovakia, Ukraine, and the European part of Russia).

The main data for the two regions - Europe Region 1 (North, South, and West), Europe Region 2 (East) – are presented in Table 5.1.

Table 5.1 Main data for the European regions for 2021, and projections for 2050, compiled from [18]

Parameter	Europe Region 1 (North, South, and West)	Europe Region 2 (East)
Population (2021)	454 million	292 million
Share of electricity in the total energy consumption (2021)	21%	14.2%
Total electricity production (2021)	2989 TWh	1591 TWh
Share of nuclear in the electricity production (2021)	22.5%	23.9%
Final energy consumption (2050/2021)	34.9/42.9 EJ	31.7/30.9 EJ
Final electricity consumption (2050/2021)	11.4/9.0 EJ	6.9/4.4 EJ
Total electrical capacity (2050/2021)	1531/1042 GWe	616/511 GWe
Total nuclear capacity (2050/2021)	133/100 GWe, High scenario	104/53 GWe, High
	43/100 GWe, Low scenario	63/53 GWe, Low
Total electricity production (2050/2021)	3527/2989 TWh	2186/1591 TWh
Nuclear electricity production (2050/2021)	1092/674 TWh, High scenario	816/380 TWh, High
	353/674 TWh, Low scenario	492/380 TWh, Low

According [18] for Europe Region 1 (North, South, and West) the total electricity production is projected to increase by about 8% by 2030 (vs 2021) and 18% by 2050 (vs 2021). The nuclear electricity production is projected in two scenarios: in High an increase by 8% in 2030 (vs 2021) and by 62% in 2050; in Low the nuclear share will decrease with 12% in 2050 (vs 2021).

For Europe Region 2 (EEC) the total electricity production is projected to increase by about 11% (2030 vs 2021) and by about 37% (2050 vs 2021). Two scenarios are formulated for the nuclear (High and Low). In the high case, nuclear electricity production an increase of 22% (2030 vs 2021) is projected and a doubling by 2050 (vs 2021). In the Low scenario, nuclear electricity production is projected to increase by 5% (2030 vs 2021), and by 29% (2050 vs 2021).

These parameters may be used to discuss the plausibility of the scenarios defined in Section 4.

Plausibility

The plausibility of the defined scenarios for nuclear development in the European Union (EU) by the horizon of 2050 (Nuclear Status Quo, Nuclear phase-out, Nuclear and Renewables Synergy, Nuclear Renaissance) can vary depending on a range of factors such as the energy policies evolution, technological advancements, political will, public opinion, frequency and level of crisis.

The discussion on the plausibility is summarized in Table 5.2, including the identification of the main factors affecting plausibility.

Table 5.2 Discussion of the plausibility for the defined scenarios

Scenario	Plausibility	Factors affecting plausibility
Nuclear Status Quo (NSQ)	EU would continue with its existing nuclear capacity and not significantly expand or reduce it. The extension of the operational life of existing nuclear plants is plausible considering the economics (acceptable investment for a prolongation with 20-30 years of the energy production). The political support for maintaining the current nuclear energy mix is plausible for most of the nuclear countries due to the significant contribution of nuclear to free carbon energy and the insufficient rate of renewable implementation towards the climate objectives. The energy security is a high priority in the EU context and the concept of diversification of energy sources will keep the nuclear power at the current share in the energy mix. The waste management issues will remain important, but not critical, since in some countries, such as in Sweden and Finland, progress in finding sites for deep geological repositories for nuclear waste are already done.	Public and political support for nuclear power, including for the new investments Safety standards and regulatory hurdles for LTO and new plants
Nuclear phase-out (NPO)	Based on the existing EU policies a fast development of renewable is expected. Due to the unsolved issues of nuclear power (waste management, risks, high cost of investment, long period until return of investment) and following the model already announced, such as the Germany's plans, a gradual phase out will be spread in the EU. The EU main priority is in favor of the development of renewables, and some countries are strongly against nuclear development in EU (Germany, Austria,	The availability and affordability of alternative energy sources The ability to maintain grid stability during the transition. The demonstration of the sustainable solution for nuclear waste disposal The difficulties in the acceleration of renewable implementation The support of Central and East

	Luxembourg).	European countries for nuclear power development
Nuclear and Renewables Synergy (NRS)	This scenario envisions a complementary role for nuclear and renewable energy sources. The plausibility is supported by the diversification of energy sources, by complementarity between nuclear and renewables (stability vs intermittency). Both alternatives need energy storage, even an adaptation of nuclear by the development of SMRs systems may improve the situation. NRS could be plausible if it gains support as a means to provide reliable baseload power while integrating intermittent renewables. Also, the plausibility is supported by the decarbonization policies, strategies and programmes at European and national level.	The development of grid infrastructure (decentralization and smart grids) and storage solutions to accommodate high share of renewables. The development of thermal storage for nuclear. The development of advanced nuclear technologies, such as small modular reactors, that are flexible and can load-follow. The discovering of new reserves of gas (or exploitation of shale gas in EU) The success of CCS implementation
Nuclear Renaissance (NR)	The NR scenario implies a significant expansion of nuclear power capacity. The plausibility of NR is driven by increased political support and investments, stimulate by the success in implementation of the SMRs at the horizon of 2040, and the readiness of Generation IV system proving high performance solutions in sustainability.	The high costs of the implementation of SMRs in the initial phase (until the achievement of serial production) Public opposition in a set of EU countries vs the public support in other countries Support for a political climate that considers nuclear energy as a priority solution to climate change. Needs to build new regulatory frameworks. The advancements in nuclear technology The ability to secure financing for new nuclear projects.

Some elements of plausibility may be derived from [19]. The role of nuclear power is discussed in the context of the assessment of the mitigation scenarios exploring different strategies to meet climate goals (considered by IPCC Group III AR6). A total of 1815 scenarios are considered, all of them built to satisfy the constraint of 1.5–2°C and simulated by different computer tools at global level.

The analysis of these scenarios [19] concluded:

(1) the electrification is a priority, at the level of 2050 a strong growth in electricity with low growth or decline in overall energy demand is necessary to follow the scenarios' constraints,

(2) the electricity mixes will be based on the free-carbon alternatives, with much more nuclear and renewables,

(3) only few scenarios consider the phase-out of nuclear,

(4) many scenarios are predicting a substantial expansion of nuclear (at least 2 times, 2050 vs 2030),

(5) an increased role of hydrogen as an energy vector is appreciated,

(6) however, the options for nuclear heat and hydrogen are low represented in the scenarios.

In summary, the plausibility of these scenarios for nuclear development in the EU by 2050 is acceptable in the context of existing uncertainties at the level of technological evolutions, and possible political options.

Looking to the level of the member states of the EU, the energy future may likely involve a mix of these scenarios, with some countries opting for phase-out, others maintaining the status quo, and some exploring a combination of nuclear and renewables, and a nuclear renaissance would require substantial changes in current policies and public sentiment.

Narratives

The narrative concept is the essence of what a vision or story is about and what it aims to communicate. In the following for each of the defined scenarios (Nuclear Status Quo, Nuclear phase-out, Nuclear and Renewables Synergy, Nuclear Renaissance) a narrative is created.

Steadfast Energy: Nuclear Status Quo in the EU (2050)

In 2050, the European Union has developed a highly advanced and sustainable energy system. The carbon-neutrality was achieved based mainly on a fast implementation of renewable energy sources like solar, wind, and hydropower. Energy efficiency and conservation is playing a pivotal role, and enhanced cross-border energy connectivity and digitalization of the grid is acting. In a context with climate change ever more pressing and increased needs for secure and low-carbon energy, some of the EU member states have maintained a steadfast course, advocating for the preservation of nuclear energy as a critical part of the energy mix.

This scenario, referred to as "Nuclear Status Quo (NSQ)", sees these countries choosing to continue with their existing nuclear capacity without significant expansion or reduction.

A Heritage of Nuclear Power

The roots of the NSQ scenario can be traced back to the 20th century when several EU nations invested heavily in nuclear power. France, for instance, continued to be a nuclear energy pioneer, relying on its extensive fleet of reactors. Belgium, Sweden, and Finland also maintained their nuclear commitments. The long-standing experience with nuclear power and rigorous safety protocols allowed these countries to continue operating their aging nuclear plants safely and efficiently.

Extended Plant Lifespans

To meet the energy demands while reducing carbon emissions, NSQ countries embarked on efforts to extend the operational life of their existing nuclear plants. They invested in plant modernization, safety upgrades, and research into next-generation reactors. These measures helped prolong the use of their nuclear facilities while ensuring that they meet the highest safety standards.

Challenges and Solutions

Although the NSQ scenario was not without challenges (for example the economic penalties due to the limited flexibility of nuclear in the context of high variable production), the countries dedicated substantial resources to address them. One significant issue was nuclear waste management. These nations collaborated on advanced solutions, including deep geological repositories, to safely store radioactive waste for the long term. Additionally, public engagement and awareness campaigns aimed to maintain the support and confidence of the people in nuclear energy's safety and benefits.

A Balanced Energy Mix

While holding onto nuclear energy as a core element of their energy mix, NSQ countries simultaneously invested in renewable energy sources and energy efficiency measures. This approach allowed them to balance the need for reliable baseload power with the increasing importance of intermittent renewables. Grid flexibility and smart technology integration helped ensure a stable and sustainable energy supply.

Global Climate Leadership

By 2050, the EU countries following the NSQ scenario had become leaders in climate action. They achieved substantial reductions in carbon emissions while maintaining grid reliability and energy security. The continued use of nuclear energy proved essential in achieving the EU's climate goals, as it provided a stable, low-carbon source of electricity.

Steady Energy Future

The Nuclear Status Quo scenario demonstrated the importance of maintaining a diverse and balanced energy mix in the pursuit of a sustainable, low-carbon future. By the year 2050, several EU countries had proven that a pragmatic and well-regulated approach to nuclear energy could be a vital component in the broader fight against climate change. As the EU moved forward, the NSQ scenario highlighted the value of nuclear power as a steadfast pillar of the European energy landscape.

Evolving Energy: Nuclear Phase Out in the EU (2050)

Despite the formidable technological and socioeconomic challenges to maintain a high pace of RES development, in EU (2050) the implementation of renewables is a great success demonstrating the high adaptability of the energy system to a new type of energy generation and consumption. The success is based on technological innovation especially in energy storage and smart grid management, investment opportunities, international cooperation, policy commitment, and energy efficiency broadly implemented.

The Nuclear Phase-Out (NPO) scenario marked a significant shift in the EU's approach to nuclear energy. In this scenario, most of the member states had made the decision to gradually phase out nuclear power, seeking alternative sources of energy to meet their environmental and energy security goals.

A Paradigm Shift

The NPO scenario was initiated by a growing awareness of the risks and challenges associated with nuclear energy. Influential EU nations, such as Germany and Spain, led the way in adopting a nuclear phase-out policy. These countries cited concerns about nuclear safety, radioactive waste management, and the desire to embrace a more sustainable, decentralized energy system.

Decommissioning and Transition

One of the central aspects of the NPO scenario was the decommissioning of existing nuclear power plants. This process was carefully planned to ensure the safe shutdown of reactors and the management of nuclear waste. Funds were allocated to support the retraining and re-employment of workers affected by the closure of nuclear facilities.

Renewables and Energy Efficiency

NPO countries invested heavily in renewable energy sources and energy efficiency measures. Wind, solar, and hydroelectric power played a significant role in the transition away from nuclear energy. National grids were upgraded to accommodate intermittent renewables and maintain energy security.

Public Support and Engagement

A critical factor in the success of the NPO scenario was the broad public support for transitioning away from nuclear energy. Governments engaged in extensive public awareness campaigns, educating citizens about the benefits of renewables, energy efficiency, and the need for nuclear phase-out. Grassroots movements and environmental organizations actively participated in shaping energy policies.

Achieving Carbon Neutrality

By 2050, the NPO countries had significantly reduced their carbon emissions, in line with the EU's ambitious climate goals. The combined efforts to phase out nuclear energy and expand renewables demonstrated that a sustainable energy future could be realized. These nations were celebrated for their progress toward achieving carbon neutrality while ensuring a safe and reliable energy supply.

A Transformative Energy Transition

The Nuclear Phase-Out scenario served as a testament to the power of political leadership and public engagement in reshaping energy policies. By the year 2050, EU countries that had chosen the NPO path had successfully transitioned away from nuclear power, embracing renewable energy sources and energy efficiency. The scenario illustrated that with vision, determination, and robust planning, it was possible to achieve a carbon-neutral, secure, and sustainable energy future. The Nuclear Phase-Out scenario symbolized a profound transformation in the European energy landscape, reflecting the commitment of these nations to environmental stewardship and a cleaner, greener future.

Harmony in Power: The Nuclear and Renewables Synergy in the EU (2050)

In the year 2050, the European Union had embraced a visionary approach to its energy mix, one that harmoniously combined nuclear power with renewables. The Nuclear and Renewables Synergy (NRS) scenario emerged as a pragmatic solution to address the need for reliable baseload power while reducing carbon emissions, ensuring energy security, and promoting a sustainable future.

The Coexistence of Nuclear and Renewables

The NRS scenario was grounded in the recognition that nuclear power and renewable energy sources could coexist synergistically. Several EU countries, including France, Sweden, and Finland, had spearheaded this approach. They acknowledged that nuclear energy provided steady baseload power, while renewables like wind, solar, and hydropower contributed variable, yet abundant, clean energy.

Modernizing the Nuclear Fleet

To achieve nuclear and renewables synergy, NRS countries invested in modernizing their nuclear fleets. Aging reactors were upgraded for enhanced safety, efficiency, and flexibility. New nuclear technologies, such as small modular reactors, were integrated to allow load-following capabilities, ensuring compatibility with intermittent renewables.

Grid Flexibility and Energy Storage

Grid infrastructure was revamped to accommodate the intermittent nature of renewables. Advanced grid management systems and energy storage solutions were implemented to balance the energy supply and demand effectively. Energy storage technologies, including large-scale batteries and pumped hydro storage, played a pivotal role in maintaining grid stability.

Public Support and Technological Advances

One of the NRS scenario's cornerstones was the strong public support it garnered. Comprehensive public engagement campaigns educated citizens about the synergy between nuclear and renewables. Simultaneously, technological advancements in both nuclear and renewable sectors were celebrated, fostering confidence in this integrated approach.

Decarbonization and Climate Leadership

By 2050, the NRS countries had made substantial progress in decarbonizing their energy sectors. Carbon emissions had dramatically reduced, positioning the EU as a global leader in the fight against climate change. The synergistic approach allowed these nations to maintain energy security while achieving their climate goals.

A Visionary Energy Future

The Nuclear and Renewables Synergy scenario symbolized a forward-thinking, comprehensive approach to energy policy. By 2050, EU countries that embraced this scenario had successfully harnessed the combined power of nuclear and renewables, ensuring reliable, low-carbon energy, and grid stability. The synergy approach not only met the energy needs of the EU but also exemplified the global leadership of these nations in addressing the climate crisis. It was a powerful reminder that by embracing innovation, public support, and integrated strategies, a harmonious and sustainable energy future could be achieved.

The Nuclear and Renewables Synergy scenario served as an inspiration for the world in the transition to a clean and secure energy landscape.

Nuclear Renaissance: A Resurgent Energy Vision for the EU (2050)

In 2050, the European Union embarked on an ambitious energy journey, spearheading a Nuclear Renaissance (NR) scenario. This vision involved a significant resurgence of nuclear power, driven by a recognition of its crucial role in addressing climate change, ensuring energy security, and promoting technological innovation.

A New Beginning

The NR scenario marked a departure from previous nuclear policies. EU member states, such as the Poland, Slovakia, Romania, Bulgaria, and Hungary, led the resurgence, advocating for a nuclear renaissance as a linchpin in their energy strategies. They viewed nuclear power as the linchpin to achieving deep decarbonization while maintaining a reliable energy supply.

Advanced Reactor Technologies

Central to the Nuclear Renaissance was the development and deployment of advanced nuclear reactor technologies. Small modular reactors (SMRs), fast breeder reactors, and thorium reactors were among the innovative designs that found a place in the new energy landscape. These reactors promised improved safety, efficiency, and reduced nuclear waste.

Strengthening Safety and Waste Management

Safety and waste management were paramount concerns in the NR scenario. Stringent safety measures were integrated into the design and operation of advanced reactors. Simultaneously, robust strategies for nuclear waste management, including advanced recycling techniques and secure storage, were developed.

Public Engagement and Acceptance

Public engagement was a linchpin of the NR scenario. Extensive campaigns were conducted to inform and engage citizens in the nuclear renaissance. Transparency, rigorous safety standards, and community involvement played pivotal roles in fostering public acceptance of nuclear power.

Climate Leadership and Energy Security

By 2050, the EU countries championing the Nuclear Renaissance had made substantial progress in reducing carbon emissions while ensuring energy security. Nuclear power, with its reliable baseload capabilities, played a crucial role in grid stability and carbon-free electricity generation, positioning these nations as leaders in climate action.

A Visionary Energy Resurgence

The Nuclear Renaissance scenario showcased the capacity of visionary energy policies to reshape the European energy landscape. By 2050, EU countries embracing this scenario had effectively harnessed the power of advanced nuclear technologies achieving their climate goals, and ensuring energy security. This resurgence of nuclear energy was a testament to the potential of innovation, public acceptance, and forward-thinking policies in shaping a clean, reliable, and secure energy future. The Nuclear Renaissance scenario marked a new beginning in the EU's energy journey, symbolizing its global leadership in addressing the challenges of the 21st century.

Further steps

This report will be circulated to collect remarks on the proposed scenarios and to introduced new considerations. The common activities of WP1 (A collaborative assessment of (imagined) energy worlds) and WP2, (Assessment of the sustainability of the whole cycle of nuclear power) will include discussions of the scenarios and formulation of recommendations for the exploitation process, including the identification of potential beneficiaries. An iterative process to update the scenarios is possible based on this feedback and is also done in case of any significant new available information or change in circumstances.

The testing of the scenarios is a long process after the final definition of them. It may be achieved by using computer tools to simulate scenario evolutions in the possible context of the energy market, trying to test the resilience of the scenarios across multiple future conditions.

Finally, some possible beneficiaries such as energy planning organizations, national and European decision makers will explore the possible impacts of their strategies and plans in the context of different scenarios to identify vulnerabilities, opportunities or needs for change. The real value of defined scenarios is to provide decision-makers with a more comprehensive understanding of uncertainties and their potential impacts.

6 Conclusions

(C1) Predicting the future decades is a very challenging activity due to the complexity of interconnected factors, such as technological advancements, geopolitical shifts, environmental changes, and socioeconomic dynamics, which introduce uncertainty and make accurate forecasts highly elusive. Scenarios serve as valuable experiments in understanding future visions by allowing us to explore diverse, plausible futures and their implications. By crafting and analyzing these hypothetical narratives, we can gain insights into the potential consequences of various decisions and trends, helping us make more informed and adaptable long-term strategies.

(C2) The building of the scenarios is based on a classical methodology whose main steps are: identification of key drivers, defining the alternative scenarios, checking plausibility and consistency of the defined scenarios, construction of the narrative for each plausible scenario. In a second phase an iterative process to discuss the scenarios with stakeholders may lead to tuning or update based on new information and new perspectives. The testing of the scenarios will seek to understand how the strategic planning performs under each scenario, and will discuss the resilience of scenarios across multiple future conditions. Finally, the value of the scenarios will be demonstrated in practice if their use will support the decision-makers for a more comprehensive understanding of the future, the potential impacts of different factors and contexts, including the effect of the associated uncertainties. These activities are connected with the future activities dedicated to the exploitation of the ECOSENS's results.

(C3) The role of nuclear power in the EU at the horizon of 2050 is strongly influenced by evolutions in the energy sector in terms of energy demand (especially for electricity), and 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 context or circumstances of the EU. To reduce complexity, six of the key factors were considered to have a clear impact (generally high), identical with the normative scenarios developed to guide the strategies and plans. The other six key factors may have a broader range of impact (discretized into three scenarios – high, medium, and low impact). Even in this case, the complexity remains very high and the reduction to a reasonable number of scenarios was necessary.

(C4) Four scenarios were defined: Nuclear Status Quo (NSQ), Nuclear Phase-Out (NPO), Nuclear and Renewables Synergy (NRS), and Nuclear Renaissance (NR). The NSQ is a continuation of the current tendency, with nuclear development keeping its pace, not much influenced by an acceleration of renewables or by the competition with other technologies. The NPO describes a gradual phase-out of nuclear power, with no new nuclear project. Some sub-scenarios were defined in accordance with the speed of phase-out: (NPO1) Fast phase-out (in the short term, following anti-nuclear vision, to be reached in 2040-2050), (NPO2) Moderate phase-out (progressively to be reached in 2050-2060), (NPO3) Slow phase-out (no new build, phase-out by end of life of existing NPPs). 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. The 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. 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 needs), and using dominantly gas to balance peak consumption, (NRS2) a combination of RES (dominantly) with nuclear for security of supply and thermal storage, and (NRS3) dominantly RES will be supported by nuclear (base load) and storage using batteries, thermal storage and hydrogen production. The last scenario, NR, envisions a renewed and expanded role for nuclear energy as a key pillar of the EU's energy strategy. The development of nuclear is accelerated by the new technologies (SMR and Gen IV). 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 Low 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).

(C5) The plausibility of the four defined scenarios was discussed and a set of factors influencing this plausibility was identified, including the public and political support, safety standards and regulatory hurdles for LTO and new plants, availability and affordability of alternative energy sources, ability to maintain grid stability during the energy transition, demonstration of sustainable solution for nuclear waste disposal, pace of the renewable implementation, development of grid infrastructure and storage solutions, development of SMRs and Gen IV systems, discovery of new reserves of gas, success of CCS implementation, investment costs for the implementation of the SMRs until the serial production stage, the ability to secure financing for new nuclear projects. A complex landscape results from the effectivity of these factors and their combinations, creating a diversity of possible situations. However, the selected scenarios offer to decision-makers relevant possibilities for the future development of nuclear power. Based on future discussion with different stakeholders an integration of other perspectives remains a valuable possibility to increase the plausibility.

(C6) The narratives associated with the four defined scenarios are developed as: (1) Steadfast Energy: The Nuclear Status Quo in the EU2050, (2) Evolving Energy: The Nuclear Phase Out in the EU2050, (3) Harmony in Power: The Nuclear and Renewables Synergy in the EU2050, (4) Nuclear Renaissance: A Resurgent Energy Vision for the EU2050. These narratives are useful for the understanding of decision-makers and to communicate with different audiences.

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