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French nuclear power. A historical and quantitative assessment of sustainability.

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Abstract

Questa tesi intende valutare se l'energia nucleare sia stata una scelta sostenibile per la sicurezza energetica francese di lungo periodo. Attraverso un approccio quali-quantitativo, combina letteratura scientifica, fonti istituzionali e dati europei sui prezzi dell'elettricità. Il caso francese mostra il ruolo del nucleare come fonte low-carbon e strumento di sovranità energetica, industriale e politica. Sul piano ambientale, il nucleare presenta basse emissioni, ma richiede attenzione per acqua, rifiuti e decommissioning. Sul piano economico, il parco storico risulta competitivo, mentre i nuovi progetti restano esposti a costi e ritardi. L'analisi evidenzia una correlazione negativa descrittiva tra quota nucleare e prezzi elettrici, soprattutto in Francia. Tuttavia, i prezzi dipendono anche da tasse, rete, gas, regolazione e struttura dei mercati energetici nazionali. La tesi conclude che il nucleare francese è sostenibile solo se integrato in un sistema low-carbon più flessibile e diversificato.

This thesis assesses whether nuclear power has been a sustainable choice for French long-term energy security. Using a mixed qualitative and quantitative approach, it combines literature review, institutional sources and European electricity price data. The French case shows nuclear power as both a low-carbon source and an instrument of energy, industrial and political sovereignty. Environmentally, nuclear power has low life-cycle emissions, but raises concerns over water use, waste and decommissioning. Economically, the historical fleet appears competitive, while new projects remain exposed to high costs and delays. The analysis finds a descriptive negative correlation between nuclear share and electricity prices, especially in France. However, prices also depend on taxes, network costs, gas prices, regulation and national market structures. The thesis concludes that French nuclear power is sustainable only within a more flexible, diversified and low-carbon system.

Introduction

In recent years, nuclear energy has returned to the centre of the European energy debate. This renewed attention is mainly linked to the growing relevance of energy security in a context marked by geopolitical instability, fossil-fuel price volatility and increasing uncertainty over the availability of strategic natural resources such as oil and natural gas. The energy crisis that followed the Covid-19 pandemic and Russia's invasion of Ukraine showed the vulnerability of energy systems highly dependent on imported fossil fuels. In this framework, ensuring a stable, affordable and low-carbon electricity has become a central energy policy priority. Nuclear power occupies a specific position within this debate because it can provide large amounts of continuous electricity, reduce exposure to fossil-fuel price volatility and contribute to decarbonisation. At the same time, it raises important questions concerning costs, safety, radioactive waste, water use, decommissioning and public acceptance.

France represents a particularly relevant case study for analysing these issues. Unlike many other European countries, France has historically built a highly nuclear-based electricity system, supported by strong state planning, industrial coordination and long-term strategic objectives. Nuclear power in France has never been only an electricity-generation technology. It has also been connected to energy independence, national sovereignty, industrial policy and strategic autonomy. For this reason, the French nuclear pathway makes it possible to investigate whether nuclear energy can be interpreted as a sustainable long-term choice for energy security, rather than simply as a low-carbon electricity source.

The main research question of this thesis is therefore the following: to what extent has nuclear power been a sustainable choice for French long-term energy security, especially when assessed through its economic costs, environmental impacts and the key political decisions that shaped its development? This question requires a broad interpretation of sustainability. In this work, sustainability is not analysed only in terms of carbon emissions, but through three interconnected dimensions. The first is environmental sustainability, including life-cycle emissions, water consumption, radioactive waste, spent fuel management and decommissioning. The second is economic sustainability, concerning the cost of nuclear electricity, the Levelized Cost of Electricity, final electricity prices and the possible relationship between nuclear reliance and more competitive electricity prices. The third is political and strategic sustainability, referring to energy sovereignty, security of supply, state intervention,

industrial planning and the civilian-military nexus that has historically characterised the French nuclear programme.

The historical dimension is fundamental for understanding the French case. The French nuclear model emerged after the Second World War, in a context of reconstruction, technological ambition and search for national autonomy. The development of civilian nuclear power was closely linked to broader strategic objectives, including the military dimension of nuclear technology and the desire to strengthen France's international position. Institutions such as the CEA and EDF played a decisive role in building an integrated nuclear system, covering research, reactor development, fuel-cycle activities, electricity generation and later waste management and safety governance. This institutional structure made possible the rapid development of the French nuclear fleet, especially after the oil shocks of the 1970s, when nuclear power became a central instrument to reduce dependence on imported fossil fuels.

Methodologically, the thesis adopts a mixed qualitative and quantitative approach. The qualitative part is based on a literature review of academic sources, institutional reports and official documents, including sources from EDF, CEA, RTE, IEA, IAEA and European institutions. These materials are used to reconstruct the historical development of nuclear power, assess its environmental and economic implications, and analyse the most recent developments in French and European nuclear policy. Moreover, emphasis is given to recent sources for the sections concerning the relaunch of nuclear energy, the EPR2 programme, the future of the fuel cycle, hybrid energy systems and Small Modular Reactors (SMRs).

The quantitative part of the thesis is based on European electricity price datasets. In particular, Eurostat data on household and non-household electricity prices are used to compare the evolution of electricity prices in selected European countries between 2007 and 2025. These data are processed through RStudio in order to produce graphs comparing France with the EU27 average and with countries such as Germany, Italy, Spain and Finland. The analysis also combines electricity price data with nuclear share data from Our World in Data and Ember, with the aim of exploring whether a higher share of nuclear electricity generation is associated with lower or more stable electricity prices. This correlation analysis is descriptive and does not claim to demonstrate causality. Electricity prices are influenced by many variables, including taxation, network costs, fossil-fuel prices, market design, renewable availability and national regulation. Nevertheless, the analysis provides useful evidence for discussing whether

nuclear power may contribute to price moderation, especially in countries where it represents a significant share of electricity generation.

The thesis is organised into four chapters. The first chapter introduces civilian nuclear energy. It explains what nuclear power is, how nuclear electricity is generated and what role it plays within the global energy mix. It also reconstructs the main historical phases of civilian nuclear development at the international level, showing how nuclear energy evolved from military and experimental origins into a commercial electricity-generation technology. This chapter provides the technical and historical background necessary to understand the subsequent analysis of the French case.

The second chapter focuses on the economic and environmental sustainability of nuclear power. It first examines the nuclear life cycle, from uranium extraction and fuel fabrication to plant operation, spent fuel treatment, radioactive waste management and decommissioning. This allows nuclear energy to be assessed beyond the sole dimension of direct CO_2 emissions. The chapter then analyses the Levelized Cost of Electricity of nuclear power in comparison with alternative energy sources, considering the importance of capital costs, financing conditions, operation and maintenance costs, fuel-cycle costs and decommissioning. Finally, the chapter develops the quantitative analysis of electricity prices in selected European countries. By comparing household and non-household electricity prices, it explores the expected correlation between nuclear share and electricity prices.

The third chapter is dedicated to the French nuclear energy pathway. It analyses the main historical phases and political turning points that shaped nuclear development in France, from the post-war period to the Messmer Plan, the expansion of the nuclear fleet, the adoption of PWR technology, the role of the oil shocks and the development of the fuel cycle. It also examines the current role of nuclear power within the French energy mix, showing how it contributes to low-carbon electricity production, energy independence and security of supply. The chapter then considers recent developments in the French energy sector, including the 2022 nuclear availability crisis, the recovery of nuclear generation, the EPR2 programme, the new PPE3 orientation and the shift from previous objectives of nuclear reduction towards a renewed strategy of nuclear revival.

The fourth chapter places nuclear power within the broader context of the energy transition. It first analyses the European governance framework as both a constraint and an opportunity for nuclear energy, considering nuclear safety rules, radioactive waste obligations, radiation protection standards and the EU taxonomy. The chapter then explores the evolving role of nuclear power within hybrid energy systems, where nuclear is no longer considered only as a traditional baseload source, but as one component of a more flexible and diversified low-carbon electricity system. Finally, the chapter focuses on Small Modular Reactors, discussing the European push for their development, their possible applications, their realistic deployment timelines and the uncertainties related to costs, licensing, supply chains and financing.

Overall, the thesis aims to show that the sustainability of French nuclear power cannot be evaluated through a single indicator. Its low-carbon profile is a major advantage, but it must be balanced against economic costs, radioactive waste, water use, technological risks and long-term institutional responsibilities. At the same time, the French case shows that nuclear energy has contributed significantly to energy security, electricity system stability and reduced dependence on imported fossil fuels. The key issue is therefore not whether nuclear power is simply sustainable or unsustainable, but under which economic, environmental and political conditions it can support a secure and low-carbon energy transition.

I. Civilian nuclear energy

1.1 Nuclear electricity production and its role within the energy mix

Nuclear energy is a form of energy extractable from atoms through fission or fusion. Nuclear fission releases energy, allowing nuclear reactors' operations and, potentially, the triggering of the atomic bomb. As the atomic bomb produces an unstable and uncontrollable reaction, a moderator can reduce neutrons' speed and stabilize the reaction. Nuclear fission produces heat, which is used to generate steam, that in turn runs the turbine. The fission happens in the core, therefore internally there's the fuel, which is the uranium predisposed for the reactor. The existence of a moderator enables the slowing down of neutrons and their effective interactions with atoms, and it allows a better control of the reaction. Furthermore, the coolant function is to flow among fuel elements to subtract the heat produced during the process. Near the core, a system of metal rods allows a self-sustained chain reaction, regulating the produced power and, if necessary, the potential shutdown. The core is enclosed inside a building called *containment structure*, which is useful to retain possible spills during accidents. A nuclear power plant unit operates similarly to a conventional thermal power plant: steam rotates turbines, which covert thermal energy into mechanical energy and power the alternator which generates electricity. The conversion of the heat produced through nuclear fission into electricity offered a way to generate large amounts of stable power, while reducing dependence on fossil fuels. The basic functioning of a nuclear reactor helps clarify the reason for which nuclear power entered the debate on energy security. Nowadays, the average global temperature has been recorded to have increased between 0.4°C and 0.8°C over the past century, and it is projected that by the year 2100, it could rise further between 1.4°C and 5.8°C. Electricity generation and heating systems are responsible for 25% of CO_2 emissions. Hence, implementing policies that promote the use of nuclear energy, rather than relying on non-renewable fossil fuels, could play a crucial role in a significant reduction of related emissions. This source of energy enables countries to meet energy demands, while contributing to the long-term reduction of CO_2 emissions. Moreover, nuclear-generated electricity is competitively priced, owing to limited dependence on uranium, a relatively abundant fuel whose extraction is less exposed to global shocks. At its current rate, global energy production from renewable energy sources (RES) is insufficient to meet world's energy demand alone. Indeed two-thirds of total greenhouse gas emissions come from production and consumption of energy. The substitution of fossil fuels with clean energy sources for electricity generation is the key strategy to combat global CO_2 emissions. Wind and

solar power plants face long-horizon renewability constraints tied to finite planetary mineral reserves, end-of-life recycling challenges, and the system costs of variability. In this context, nuclear energy contributes to mitigating high energy costs and decreasing national reliance on external energy sources. Advanced nuclear power plants rely on abundant forms of uranium and thorium which are turned into usable fuel. This process enables an effective enlargement of the resource base and lengthening fuel availability from decades to potentially centuries or longer. An opposite view emerges in the context of wind and solar, which depend on lithium, cobalt and rare earths, that are finite and geographically concentrated minerals. In clean energy-driven scenarios, such as OECD countries, nuclear energy significantly aids in mitigating pollution. If we look into he French's case, data from the 1960s to the early 2000s indicate a long-term inverse relationship between nuclear energy consumption and carbon emissions (Iwata et al., 2010). It is widely acknowledged that nuclear energy can effectively reduce production-based emissions, while it doesn't have any effect on consumption-based emissions. Notably, the solely deployment of it may present limitations in effectively addressing environmental degradation. Certain empirical studies have stated that 1% increase in nuclear consumption leads to 0.30% increase in carbon emissions (Sadiq et al., 2023). However, this may be attributed to the relatively limited investments made by the nuclear-utilizing countries included in the study. In fact, the current level of investment required to offset environmental externalities has to be achieved yet. Although nuclear energy is considered a low-carbon source, it is important to account for the indirect emissions produced during the construction and deployment of nuclear power plants, which contribute cumulatively to a country's total emissions. Even within OECD countries framework, nuclear energy consumption has not led to a significant reduction in CO_2 emissions. Consequently, it is suggested that greater investment is needed to strengthen the role of nuclear power in emission reduction efforts (Danish et al., 2022). Nuclear power supplies roughly 10% of global electricity, nearly 20% in advanced economies. Historically, it has been a major source of carbon-free generation, it faces country-specific challenges but retains substantial potential to support power-sector decarbonisation. By providing system stability and limited load-following capability, nuclear plants bolster electricity security and complement decarbonisation pathways. The value of these services increases with higher shares of variable renewables such as wind and solar PV. Although capable of supplying low-carbon baseload, nuclear power struggles in some markets due to substantial capital intensity, long development horizons, and recurrent delays, alongside

persistent public opposition. Underinvestment or retirements would likely be backfilled by higher-emitting sources, adding billions of tonnes of CO_2 (IEA, 2025). Policymakers will be able to fully exploit the potential benefits associated with this energy source in their countries, only through a substantial rise in the share of nuclear energy within the overall energy mix. The deployment of this energy source is highly context dependent. In developed economies, increasing its share in the energy mix tends to realize the full range of benefits, whereas in developing economies it should not be the main priority during the initial phases of energy transition. Hence, progress toward net-zero goals generally requires the gradual substitution of oil and gas with RES. As a point of comparison, under typical operating conditions a 1,000-MW coal-fired unit consumes on the order of 2 Mt of coal per year, whereas a nuclear plant of comparable capacity uses approximately 190 t of natural uranium. Uranium is the source of nuclear power, which is still widely available worldwide. However, nuclear power is not entirely emissions-free on a lifecycle basis: plant construction, the fuel cycle and operations consume energy and generate CO_2. Then, the decline in CO_2 presence in the atmosphere is driven primarily by the displacement of fossil-fuel generation. As an already commercialised technology, nuclear energy can partially span the interim between fossil dependence and large-scale renewable penetration. We can state that nuclear electricity remains a strategic component of long-horizon sustainability policies. It owns a pivotal role for the generation and dispatch of low-carbon electricity with near-zero direct and low lifecycle emissions. The reliability on nuclear permit to phase out or at least diminish coal and gas and to balance the variability that characterize RES (Sadiq et al., 2022).

In the recent years, research for the implementation of hybrid energy systems has emerged as a strategic and cost-effective approach. This system aims to potentially address the intrinsic trade-offs of clean energy sources such as renewables and nuclear power within the framework of energy policies. Policymakers will be able to leverage the complementary strengths of both technologies while minimizing the drawbacks associated with their isolated deployment. A hybrid energy system is made by integrated facilities that combine nuclear reactors, renewable energy generation and industrial applications. The expected benefits are the enhancement of grid flexibility, the achievement of significant reductions in greenhouse gas (GHG) emissions and the optimization of return on capital invested. Although nuclear energy alone may be insufficient to satisfy global energy demand, its exclusion from the energy mix could significantly hinder the achievement of these objectives (Abu-Khader, 2009). According to

Augutis et al. (2015) an optimal allocation of energy sources should comprise 50% renewables, 30% nuclear energy, and 20% natural gas, which is comparatively less polluting than oil. The combined technologies scheme contributes to alleviating the burden on the infrastructure of any single energy resource, avoiding it from exceeding critical threshold levels. All things considered, part of the literature argue that nuclear energy does not effectively contribute to sustainability goals, as it fails to significantly reduce carbon emissions and it is considered incompatible with renewable energy integration. Moreover, it has been suggested that nuclear initiatives may even lead to increased emissions in developing economies (Sovacool et al., 2020). On the other hand, nuclear energy decreases a country's reliance on imported fossil fuels. Indeed, reduced dependency on imports enables improvements in energy security and reduction in supply disruptions and price volatility. Nuclear-related policies facilitate the transition toward modernization by providing a stable and reliable electricity supply. The provision of nuclear energy drives industrial growth, infrastructure development, and urbanization, ultimately contributing to broader socio-economic progress. The realization and deployment of positive externalities can occur through a long-term sustainable pathway, as many of the beneficial potentials associated with the utilization of this energy source do not exert significant environmental impacts in the short term (Zheng et al., 2024). Although nuclear remains a key topic in policy agendas with potential contributions to future supply, recent years have seen modest net expansion and progress toward environmental-protection targets remains incomplete across many jurisdictions.

1.2 The evolution of civilian nuclear power

The history of nuclear energy is strictly connected with Second World War, not only due to its role to terminate the conflict but even for the acceleration of the scientists' endeavour. The threat of Nazism and the worrying German expansionism shifted atomic research towards the nuclear weapon. Nuclear development acceleration resulted from the collaboration and common effort of physicians from all over the world that worked together in the US. Only afterwards, nuclear energy was taken into consideration for the generation of electricity. In 1939, Roosevelt decided the constitution of a consultive committee of uranium. The following year it was discovered the transmutation of U-238 into a new element that was called plutonium, understood as fuel suitable for the creation of a nuclear weapon. Most scientists considered the US the only country able to ensure organisational and financial resources to achieve the

objective, even if someone considered unethical the research purposes and preferred to withdraw from military nuclear experience. During summer 1942, the project, known as the *Manhattan Project,* was entrusted to the US Army: its aim was nuclear bomb's creation through the development of technological solutions, including the production of fissile material for its realisation. The tragic epilogue happened in the August 1945 with the raid on Hiroshima and Nagasaki, which caused the death of more than 200,000 civilians by the end of the same year, also considering deaths occurred due to post-bomb radiations. The true reason behind this decision was to show to the world, especially to USSR, the destructive power of the nuclear bomb. Nonetheless, its use was justified as a means for saving an uncountable quantity of lives, who would have died without a swift end of the conflict. Civil nuclear acceleration has been heavily influenced by the international situation after the Second World War, indeed, during the Cold War, the contrast between American and Soviet blocks was played both on commercial and military fields. Primacy against the other was the natural consequence of the economic role represented by the country worldwide. During those years, the demand of electricity increased massively and, as a result, nuclear represented a great strategic opportunity for both sides. The early development took place in the US with the creation of the Commission for Atomic Energy (*USAEC, United States Atomic Energy Commission*). Despite, the authority was controlled by the Joint Committee for Atomic Energy with members from the Senate and the House to ensure parliamentary control, the Commission had a direct connection with the President. The American setting consisted in the state control over nuclear military applications, while leaving to private industry the research for electricity generation from nuclear energy. However, the use of this new energy source to produce electricity presented several challenges. There was a lack of economic motivations because of the requirement of expensive experimental phases, huge plant construction costs to bear, unpredictable revenues to face, together with the danger behind the management of this new technology. The explosion of the Soviet H bomb in 1953 brought an end to American monopoly over nuclear military applications. The initiative *Atoms for Peace* is considered the clear consequence of the unstoppable diffusion of nuclear technology and especially as an attempt to cope with the threat of Soviet Union predominance. Therefore, President Eisenhower in 1953 proposed to the United Nations the creation of an international agency for atomic energy, entitled of storage and fissile materials control. In 1954 a new atomic energy law allowed knowledge sharing and the free circulation of materials and equipment through bilateral agreements with single countries. The true reason behind the know-how

sharing was the control and inspection of worldwide nuclear materials transactions, that originated from unknown dangerous exchanges, which could have triggered global order destabilization. Even nowadays, the United States are trying to maintain a central role in limiting the proliferation and development of military nuclear capabilities within politically unstable and threatening jurisdictions, with the aim of global security preservation and regional destabilization prevention. The pathway started in the early years of commercial nuclear development was therefore marked by the strategic primacy and the technological leadership of the US. Their underlying economic interests were certainly visible: the two greatest reactor builders, General Electric and Westinghouse, covered the entire West market, at that time. The general objectives deriving from the programme *Atoms for peace* were overall cost reduction, the decrease of construction and start-up average time and the obtainment of more consistent research outcomes to face results unpredictability. This shared engagement resulted in the Conference for peaceful use, held in 1955 in Geneva, as first evidence of international cooperation for the nuclear subject. Despite the first years were connotated by great excitement, there was a huge underestimation of challenges and costs of nuclear solutions' development, complemented with too optimistic performance projections, considered the technological readiness level (TRL) at that time. In 1956 the International Atomic Energy Agency (IAEA) was created with the aim to oversee nuclear materials and technological applications and verify their compliance with security and protection international standards. The agency was supposed to encourage nuclear adoption in developing economies, supporting social and economic advancements. Alongside, European Atomic Energy Community (Euratom) was responsible of nuclear know-how dissemination, coordination of member states' research and the facilitation of investments. The main difference between IAEA and Euratom was the strict relationships with enterprises that the latter boasted, on the contrary, the first one entertained exclusively collaborative relation with participating states. Always in Geneva, in 1953, there was the creation of the European Council for Nuclear Research (*Cern*), one of the most influential international research centres. The nuclear military-civilian nexus was one of the reasons that made possible the establishment of new forms of international cooperation, as Euratom and the Atom for Peace program (Bini, E., Londero, I., 2015). In 1956 the American electricity societies were authorised to associate for nuclear power plants' realisation. These legislative advancements led to little success, as the electricity producers feared the threat of nationalisation.

In France, the first moves were made even before US and Soviet Union, indeed in 1945 there was the creation of the Atomic Energy Committee (*Commissariat à l'énergie atomique et aux énergies alternatives*). Its role was to favour scientific research and the construction and management of nuclear power plants. Shortly thereafter, in 1946, the creation of EDF (*Electricité de France*) led to the French electricity sector nationalisation. Originally, these two agencies collaborated only on a scientific research basis. In 1948, the first experimental reactor called *ZOE*, acronym of its main features (zero power, uranium dioxide, heavy water), was under operations. In 1952, it was enacted the first 5-year nuclear plan with the creation of the Marcoule site, near Avignon, where was also created a fuel reprocessing plant, useful for plutonium extraction, which represented a fundamental component for the development of nuclear weapons. Abundant raw materials were necessary to run the entire site and, for that reason, France started the exploration of uranium reservoirs in its own territory or its former colonies and in foreign countries. Eventually, uranium extraction sites were discovered in the former Limousin region and overseas deposit in the former colonies, such as Niger, where the low exploitation cost and the value of the materials resulted particularly attractive (Boyle, M., Robinson, E., 1981). The French nuclear pathway was supposed to follow three clear stages: natural uranium power plant, enriched uranium ones and finally Fast-neutron reactors (FNR). After World War Two and the progressive dismantling of its former colonial empire, France was living a period of frustration. According to the President de Gaulle and the Premier Mendès-France, the international weight of the country could be measured and enhanced via the military solutions advancements and nuclear power represented a clear opportunity. The second 5-year plan of 1957 followed the Indo-China war defeat, envisaging nuclear power plants operative in less than ten years. The key decision-making criteria was the restoration of the French political power and its re-establishment among the global hierarchies. Other from military application, electricity generation from nuclear energy was necessary to cope with coal and oil shortages resulting from colonial raw materials losses. Another reason for the development of the French nuclear programme was to show scientific knowledge and research primacy. Moreover, at the beginning, the French nuclear pathway was widely accepted with strong approval both on the civilian and military sides. Even during 1970s, protests against nuclear power did not receive enough support, as instead in other European countries, because of those early decisions. In few years, France would have become one of the most nuclearized

countries worldwide, with a constant electricity surplus, some of the most advanced research facilities and reactor engineering.

USSR started its atomic effort through the development of different nuclear technologies, both based on the same cooling system (PWR-pressurized water reactor), which differed on the type of moderator (graphite or water). The confidentiality of the Soviet military nuclear applications enforced the non-disclosure of uranium availability of the country. On the nuclear civilian side, in 1954, *AM-I (atom mirny, peaceful atom)* was the first reactor that started to produce electricity in Obninsk, near Moscow. Then, in 1956, the English reactor *Calder Hall* confirmed the possibility to produce plutonium for military solutions on one end and generate electricity on the other. This reactor was the model for the advancement and deployment of industrial-scale nuclear power plants employed for electricity production. Summarizing, nuclear power plants' realisation required significant economic resources, extended project timelines and important land requirements due to standard sites' dimensions. In this framework, countries' financial support was pivotal to cover the necessary funding requirements and to undertake projects too risky for private industry alone. The first programmes were too ambitious, the belief of rapid fossil fuels phasing-out was soon denied, as the projects' results were unforeseeable and objectives set were unachievable. Nuclear reactors technology evolved through three main phases: Generation I reactors were early prototypes built during the 1950s and the 1960s; Generation II reactors became the standard commercial fleet from the 1970s; Generation III and III+ reactors, developed from the 1990s onward, incorporated advanced safety features, improved performance and longer lifetimes. The first generation was mainly experimental and included reactors aimed at research activities, nuclear fission and production of plutonium. The second phase involved navy projects research, especially submarine propulsion for vessels' military applications, while the last phase was dedicated to electricity generation and plutonium collection for nuclear bomb purposes. The first experimental reactor was the *CP-I*, through which Fermi obtained a successful reaction, then followed by the Manhattan Project creation and the experimental site of Los Alamos. In Europe, the deployment of the first reactors prototypes happened after the Second World War, specifically with *GLEEP* (Graphite Low Energy Experimental Pile) in England and *ZOE* (Zero power, Uranium dioxide, Heavy water) in France. In parallel, USSR started plutonium production in the Urals and in 1947 it concluded a first successful nuclear bomb test. During the experimental phases, very different layout choices were taken, according to the specificities and diversity of the national actors involved

in nuclear development. Concerning the fuel, USSR and US chose enriched Uranium, while England, France and Canada preferred the adoption of natural Uranium for their supply chains. Consequentially, graphite was the moderator for France and UK reactors, while US adopted water use and Canada preferred heavy water. Unlike H_2O, heavy water contains deuterium (D_2O) instead of hydrogen, allowing to slow down neutrons while absorbing fewer of them, making it suitable for moderators that use natural Uranium. Considering the reactor cooling design, US and USSR largely promoted water-cooled configurations, Canada developed heavy-water reactors, while UK and France initially relied on gas-cooled reactors using carbon dioxide as coolant. Thereafter, the most common configuration would become water as moderator and coolant. For instance, French *UNGG* (natural uranium graphite-gas) reactors were based on a specific technological combination: they used natural uranium as fuel, graphite as moderator and carbon dioxide (CO_2) as coolant. This design allowed France to develop nuclear power without relying on American enriched uranium. For this reason, the technological decisions made during those years not only represented the best engineering solutions, but even a hidden strategic and political direction. France therefore pursued the development of UNGG to ensure its energy independence and national control over the nuclear programme.

The *Yankee Rowe* was the first commercial nuclear plant, that entered in operation in the US in 1960, with an installed capacity of 250 megawatts (Maugeri, 2006). In 1965, United Kingdom and US were the greatest electricity producers, even considering electricity coming from nuclear sources. With 3,575 GWh of nuclear electricity production, Italy covered a unique position, indeed the country didn't have reactors of own property, as well as nuclear weapon development programme. In the post-war period, Enrico Mattei aimed to make *Agip Nucleare* a leading actor within the Italian energy system, gathering nuclear development to broader ambitions of industrial modernisation and national energy autonomy. In 1960, nuclear power was also associated with the economic development of Southern Italy, as shown by the *Garigliano* nuclear power plant, a project that was part of the policies of the *Cassa per il Mezzogiorno* policies. Italy adopted American reactor technology, including the BWR (Boiling Water Reactor) model, while institutions such as *CISE*, the first Italian nuclear energy research center, contributed to both theoretical and applied nuclear research. However, the development of the Italian nuclear programme slowed down partly because of the nationalisation of the electricity sector and a lack of a unified national strategic direction. Although Italy played an important role in nuclear research and was recognised at the Third Geneva Conference on the

Peaceful Uses of Atomic Energy as one of the leading countries in nuclear electricity generation, its first three nuclear power plants relied on three different technologies. While this technological diversity could be interpreted as a form of diversification, it also reflected the fragmented and uncoordinated efforts of different actors rather than a coherent national nuclear strategy. The Italian nuclear journey was predominantly featured by the country's nuclear physics strong tradition, complemented during the post-World War II research. Although Italy was one of the first nation showing interest in developing civilian nuclear energy, the country's early retirement represented one of the first European withdrawal from nuclear ambitious energy policies. The politics and oil multinational interests, together with the anti-nuclear and environmental movements pressures dramatically influenced the abandonment of nuclear ambitions. Eventually, the 1987 referendum sanctioned the retirement from nuclear energy, with a public opinion shocked since the recent Chernobyl accident. Italy's fragmented nuclear experience reflected a wider European vulnerability: the limited access to enrichment technology and the dependence on U.S. fuel supplies, which contributed to the creation of a common framework to coordinate nuclear development and secure technological autonomy (Bini, E., Londero, I., 2015).

As already said, the main problem of enriched uranium adoption was the limited diffusion of enrichment technology in the post-war phases, due to secret agreements signed during the Second World War. Therefore, few exchanges of materials and know-how were made at that time. *Euratom* (European Atomic Energy Community) was created in 1957 to overcome these challenges by exploiting the collaboration with the US to enhance performances and reduce the costs. The United States actively supported the creation of the organization to secure a profitable export market for its industrial giants called *Westinghouse* and *General Electric*. The subsequent US-Euratom Cooperation Act of 1958 was not only market-based, because United States wanted to promote a common engagement and unify a solid pro-Western block against Soviet Union. This cooperation framework was created to foster the peaceful use of nuclear energy while keeping the international situation under control. However, the 1968 Non-Proliferation Treaty showed the emergence of proliferation risks and the growing fear of redirection of nuclear civilian technology towards military purposes. Soviet bypassed the obstacle through the reprocessing of spent nuclear fuel to obtain plutonium, a material useful for nuclear weapons fabrication. The establishment of *Eurodif* (European Gaseous Diffusion Uranium Enrichment) in 1973 represented another important step in Europe's attempt to secure

an autonomous and self-sufficient enriched uranium supply. The consortium contributed to later tensions around nuclear fuel cycle control. Initially, the member were France, Italy, Belgium, Spain and Sweden, nonetheless they withdrawn themselves shortly after the start of the project. Furthermore, the subsequent participation of Iran demonstrated how access to enriched uranium could become politically sensitive in the broader debate of nuclear proliferation. Finally, the 1974 Indian nuclear bomb test confirmed American fear concerning incognito military purposed dressed as national electricity programs. On a global scale was understood the requirement of more stringent measures in order to oversee nuclear proliferation. Indeed, India didn't face any resistance to collect plutonium from a Canadian research facility. This concern became even clearer under the Carter administration, which strengthened non-proliferation policies by questioning fast neutron reactor development, contrasting plutonium reprocessing and blocking the export of enrichment technologies. In this way, US sought to reduce the possibility that civilian nuclear programmes could be diverted toward the production of atomic weapons.

In the late 1950s, France was lagging behind other European countries, with only 1,056 GWh of nuclear electricity generation. In general terms, the American enriched uranium fuel cycle was the most widespread among the nuclear powers. In the US, the incentive to invest in this technology for private industries was the threat of public power meddling. Therefore, the first steps were characterised by an offering of reactors at discounted price, that didn't reflect any economic rational. The enhancement of the American design was supported by the Boiling Water Reactor (BWR) of General Electric and the Pressurized Water Reactor (PWR) of Westinghouse. During the 1970s the fall of oil demand and the worldwide energy conservation policies, pushed the competitiveness of nuclear to its golden age, particularly through the massive deployment of nuclear policies within Europe and the US austerity measures to avoid dependencies on foreign black gold. Oil companies were worried concerning their raw material scarcity, consequently they prompted their engagement in exploration and production activity aimed at the nuclear alternative. On the other hand, coal and mining societies became one of the most important pressure groups against atom in the years that follow. Nuclear as a new source of electric power was a novelty upheld by the industrial world shift from oil exclusively to energy source diversification, including even natural gas. Despite the opportunity given by the first oil shock of 1973, the huge expansion of nuclear was already shrinking since before the near meltdown of the Three-Mile Island nuclear reactor. Undoubtedly, this incident shed

light on the unreliability of nuclear energy as an alternative to oil and confirmed the general rethinking concerning atom energy policies. Nonetheless, the deceleration of nuclear development was the result of a general rise in plant construction costs, stricter safety and material quality requirements and the extension of production timelines. The growing concerns of major accidents damaged nuclear image, while reducing civilians' support. Despite the nuclear sites creation slowdown, during the 1970s decade were constructed approximately two thirds of the 243 nuclear power plants operating in 1980, with a total capacity of 140,000 MW (Maugeri, 2006). Only during 1980s emerged the nuclear waste disposal issue with the triggering of geological safety requirements debate for disposal sites. The first of this was operating, after several delays, in 1987 in USA (*Yucca Mountain*) and was indeed dedicated to dispose nuclear waste. Antinuclear movements strengthened themselves exploiting the opportunity given by the lack of clear disposal regulation. Their claims were driven by this legislative vacancy. The worst possible scenario that caused a further reduction in nuclear production was the happened with the Chernobyl accident of 1986, occurred during a turbine rundown test at Reactor No. 4. The purpose of the test was to determine whether the residual rotational energy of the turbine generator could temporarily supply electricity to the reactor's cooling pumps in the event of a loss of external power, before the emergency diesel generators became fully operational. However, the test was carried out under unstable operating conditions, including very low reactor power and reduced coolant flow, which contributed to a rapid power excursion and the subsequent destruction of the reactor. Just before the explosions, the reactor experienced an extreme power surge, possibly reaching around 30,000 MWt, far above its normal operating level of about 3,200 MWt. The first explosion was generated by the increase of steam and pressure, and the second one was produced by graphite burn and hydrogen explosion. The most urgent issue was the prolonged open-air release of radiation from the destroyed reactor core. For several days, smoke and radioactive fission products were dispersed into the atmosphere, while firefighters and helicopter crews involved in extinguishing the fires and covering the reactor were exposed to severe radiation doses. A containment barrier was constructed to isolate the reactor debris and reduce further environmental contamination, particularly of the surrounding soil. There were multiple and significant reasons behind the dynamic of the catastrophic event, among all the defects of control rods that caused the alteration of neutron flow and a poor containment structure that eventually led to the core fusion. Part of the responsibility is due to a lack of coordination of test team, and personnel

aimed at safety control (International Atomic Energy Agency, 1992). Inevitably, the global nuclear landscape sharply changed and led to several withdrawal and review of countries' energy mix plans. Indeed, only France, England and Japan were truly still engaged in their nuclear plans even in the early moments after the disaster. In the following years, while France became the country endowed with the most advanced reactor technology, in 1995 UK decided to terminate state aids for nuclear that were considered too costly according to Thatcherism perspective. In the aftermath of Chernobyl, the evolution toward Generation III reactors reflected an attempt to restore confidence in nuclear technology through enhanced safety systems, improved operational reliability and more standardized reactor supply chains. During the 1990s, this shift was reflected by designs in the Westinghouse's APWR (Advanced Pressurised-Water Reactor) and General Electric's ABWR (Advanced Boiling Water Reactor), whose technologies were further developed and consolidated in the following decade.

II. Nuclear energy economic and environmental sustainability

2.1 Nuclear energy life cycle

Transitioning in a more sustainable society is a process that should include the adoption of nuclear energy due to its minimal carbon emissions, the high power generated, the extraordinary energy density and its less land requirement. Through the support of renewable energy sources, it is possible to optimize the energy structure and achieve a more robust sustainability and obtain an air pollution decrease. Nuclear has also a positive impact on industrial production and energy efficiency policies, while it lowers overall generation cost and energy dependence. However, the underlying environmental potential negative effects on the environment could led to public opinion concerns and apprehensions. In support of this, a part of the literature has observed that nuclear may produce adverse impacts on ecological quality if radioactive waste management is characterized by operational inefficiency and technical incompetence. Conversely, nuclear waste recycling reduces environmental footprint, by supporting fuel re-usage activities, while promoting energy independence policies and increasing clean electricity production (Sadiq, M. et al., 2022). Nuclear energy impact on the environment should not be assessed only via its carbon dioxide measurement but even having regard to its broader ecological footprint. Indeed, the benefits of its low-carbon electricity production and energy diversification potentialities are hindered by negative externalities associated with radioactive materials management. Nonetheless, the upgrading of the safety and management processes of new nuclear energy facilities could turn those side effects and potentially decrease the overall environmental impact. Advanced reactors design, such as Small Modular Reactors (SMRs) and generation IV reactors show safety, fuel efficiency and waste management enhancements that have improved their environmental sustainability. Other two alternatives are represented by Thorium-based reactors, that displays the opportunity of less long-lived radioactive waste, and the Molten Salt Reactors (MSRs), both characterized by improved safety and waste management features. Furthermore, fusion energy, even if in its experimental phase, would be a promising limitless power source, despite one could question who would take advantage on its economisation, as the value of the legacy energy source is represented by their scarcity. The relationship between nuclear energy and the environment is complex, as nuclear power is often considered a low-carbon solution to rising global electricity demand, while its broader environmental implications extend across the entire fuel cycle. The rapid shift from the traditional fossil fuels like coal and oil to the implementation of nuclear energy solutions on

one end could reduce the CO2 emissions generated, while on the other could not be sufficient to deal with the broader environmental degradation. If we look at the Pakistan's case, the country's nuclear energy consumption from 1973 to 2017 is positively related to the presence of air pollutants in the atmosphere, thus challenging the decreasing greenhouse gas emission nexus assumption. Pakistan can still experience significant air pollution despite the use of nuclear energy because nuclear power represents only one component of the national energy mix, and its low-carbon benefits may be outweighed by the continued reliance on fossil fuels in electricity generation, industry and transport For this reason, the ecological footprint (EF) can be used as a more comprehensive measure of environmental degradation, since it includes not only carbon-related impacts but also broader pressures on land, resources and ecosystems. This indicator provides a broader measurement of the environmental impact by encompassing and quantifying built-up land, carbon, cropland, fishing grounds and forest products. According to Soto et al., nuclear energy use in the European Union increases the environmental footprint not because of the CO2 emission that are reduced, rather due to the severe impact on deforestation and air quality. A relevant point emerging from the empirical results of the researchers concerns the direction of causality between CO_2 emissions and nuclear energy generation. While nuclear power is generally associated with lower direct greenhouse gas emissions, the causality test suggests that, in the EU context, the relationship mainly operates from CO_2 emissions to nuclear generation. This means that higher levels of carbon emissions can act as a driver for countries to reconsider or strengthen nuclear energy as a less carbon-intensive alternative to fossil fuels. Nuclear power should therefore be interpreted not only as a technology capable of reducing the carbon intensity of electricity generation, but also as a policy response to the pressure created by decarbonisation targets and air pollution concerns. The life-cycle approach is particularly relevant for the French case, where nuclear power has historically reduced the carbon intensity of electricity generation, but has also created long-term responsibilities related to fuel-cycle management, radioactive waste, reactor ageing and decommissioning. France's vertically integrated nuclear system therefore needs to be assessed not only through the amount of low-carbon electricity it produces, but also through the environmental and institutional capacity to manage each stage of the nuclear chain. Nuclear energy can be considered as a low-carbon alternative during the electricity generation phase, although it cannot be assessed only at the point of production. A life-cycle perspective shows that its sustainability also depends on uranium extraction, fuel processing, plant construction,

radioactive waste management, spent fuel disposal and decommissioning. For this reason, nuclear power may contribute to reducing CO_2 emissions while still generating broader ecological impacts that must be managed through strict regulation, technological expertise and long-term institutional responsibility (Soto, G. et al., 2024).

A wise way to unlock new economic opportunities and decrease waste could be the application of circular economy principles in the decommissioning process. The average nuclear power plant lifetime is 40-60 years, however, as most of them were built between the 1960s and the 1980s the end of their operational lifespans has been delayed with extensions which go far beyond this limit. If a lifespan extension is not feasible, nuclear decommissioning will encompass the safely closing and dismantling a nuclear facility after it has reached the end of its operational life, including the removal of radioactive materials and site cleanup. The radioactive waste generated accounts only the 5% of the total operation, the remaining 95% is recyclable and potentially ready to satisfy the needs of existing plants. It's impossible to radically eliminate radioactive risk, however creating a waste hierarchy enables to classify the different materials and eventually their disposal process. In France, the radioactive waste hierarchization follows a classification based on two main criteria: the level of radioactivity and the radioactive half-life of the radionuclides contained in the waste. The main categories are very-low-level waste (TFA), low- and intermediate-level short-lived waste (FMA-VC), low-level long-lived waste (FA-VL), intermediate-level long-lived waste (MA-VL), and high-level waste (HA). This classification allows an appropriate waste management pathway, ranging from surface disposal for very-low-level and short-lived waste to deep geological disposal for high-level and intermediate-level long-lived waste (Commissariat à l'énergie atomique et aux énergies alternatives, 2017).

Category	Description
TFA	Very-low-level waste, mainly from operation, maintenance and dismantling
FMA-VC	Low- and intermediate-level short-lived waste, usually managed in surface disposal.
FA-VL	Low-level long-lived waste requiring specific long-term management.
MA-VL	Intermediate-level long-lived waste, mainly from spent fuel treatment.
HA	High-level vitrified waste from spent fuel treatment, containing most radioactivity.

Table 2.1: French nuclear radioactive waste classification (Source: Ministère de la Transition écologique, 2016)

Although public opinion's scepticism persists in this field for safety reasons, recycling waste is a crucial method for better managing resources, save disposal space and therefore the related costs. A nuclear energy life-cycle perspective must include not only uranium extraction, fuel fabrication, plant construction and electricity generation, but also the end-of-life phase of nuclear installations. Decommissioning is a particularly important stage, as it involves planning, radiological and physical characterisation, decontamination, dismantling and materials management. This phase shows that nuclear sustainability does not depend only on low-carbon electricity production, but also on the capacity to manage large quantities of materials and waste after the plant has stopped operating. Nuclear decommissioning has traditionally followed a linear "cradle-to-grave" model, in which materials are progressively classified, treated and disposed of. However, recent research suggests that circular economy principles can help reduce the environmental burden of this phase by promoting reuse, recycling, refurbishment, recovery and repurposing of materials, components, buildings and sites. To better evaluate the decommissioning or recycling options relying on environmental criteria some studies suggest integrating a Circular Economy (CE) framework with a Life Cycle Assessment (LCA) approach. This method allows to measure the impact of operations from the extraction of raw materials to the final disposal of waste. Through the integration of CE and LCA principles into nuclear decommissioning, it's possible to expect a positive contribution in the environmental, economic and social dimensions with a sustainability lens. The circular economy principles application within nuclear decommissioning represents a sustainable model of production and consumption that requires the efficient use and rationalisation of resources throughout the stage of the value chain. Applying this framework from the design stage of

nuclear installations would allow circular economy principles to be integrated across the whole nuclear life cycle. This could promote process innovation, reduce the use of new raw materials and the production of waste, and decrease both economic costs and the broader social costs associated with environmental pollution. Nevertheless, the application of circular economy principles in nuclear decommissioning remains complex. Indeed, nuclear materials reuse is limited by radiological safety requirements, verification costs, regulatory constraints and public acceptance. Even when they are technically reusable, concerns about residual radioactivity may reduce social trust and make circular practices difficult to implement. This is particularly relevant for France, where strict clearance levels enforced by the nuclear safety authority can limit the reuse or recycling of materials from decommissioned nuclear sites. Therefore, circularity in the nuclear life cycle cannot be understood only as a technical or economic issue, but also as a regulatory, social and safety-related challenge. Overall, the decommissioning phase shows that the sustainability of nuclear energy must be assessed across the whole life cycle. Nuclear power can provide low-carbon electricity during operation, but its long-term sustainability also depends on how effectively radioactive and non-radioactive materials are managed, whether waste volumes can be reduced, and whether circular economy practices can be implemented without compromising safety, transparency and public trust (Perko, T. et al., 2025).

A broader life-cycle perspective should also consider the distinction between production-based and consumption-based CO_2 emissions. Production-based emissions refer to the emissions generated within a country's territory, including those from domestic electricity production, industry and households. Consumption-based emissions, by contrast, include the direct and indirect emissions embodied in the goods and services consumed domestically, including imported products. This distinction is particularly relevant in a globalised economy, where part of a country's environmental impact may be displaced through international trade. Within this framework, the objective should be the achievement of sustainable development without additional environmental degradation by shifting towards clean energy sources for electricity generation. Nuclear energy could be even a better alternative, as generates energy continuously, with capacity factors close to 100%, and it doesn't face the RES variability constraint. Both nuclear and renewable energy sources should support the decarbonisation of the energy sector and further contributing to the planet decarbonization in the future. In addition, nuclear energy has a relevant importance in extreme clean energy scenarios, contributing to pollution and

emission mitigation, supporting environmental protection and sustainable development. According to Danish et al., a nuclear energy consumption increase of a percentage point reduces the production-based-CO_2 emissions by 0.07%. This suggests that nuclear power can decarbonise domestic electricity production, but it cannot by itself reduce the wider carbon footprint linked to imported goods, consumption patterns and global supply chains. For this reason, the life-cycle assessment of nuclear energy should be complemented by a broader carbon-accounting perspective. As a cleaner alternative, the atom energy can replace traditional energy ensuring energy security and stimulating economic growth, even if requiring further investment and intensification. (Danish et al., 2022). As already described previously, the electricity mix in France is largely dominated by nuclear power, with an energy sector responsible for a carbon intensity of 56.9 g CO_2eq./kWh. The CO_2-equivalent emissions express the climate impact of different GHGs emissions using carbon dioxide as a common reference unit. They indicate the amount of CO_2 that would produce the same warming effect, over a given time horizon, as a given quantity of another greenhouse gas or a mixture of greenhouse gases. Within this framework, the electrification of the overall energy mix is a crucial policy to decarbonise the whole energy sector. For that reason, the achievement of climate neutrality by 2050 should be pursued by bringing electricity at least at 55% of the French energy mix. The most comprehensive method to quantify the potential environmental impacts of a nuclear over its entire life cycle, from raw material extraction to the end-of-life of reactor is through the Life Cycle Assessment (LCA). Nuclear supply chain upstream activities include the extraction and milling of uranium ore to separate it from other minerals and impurities. After the extraction, the uranium is concentrated in the form of uranium dioxide, then purified and enriched to enable its use as fuel in the reactors. Since 2009, French nuclear industry has decreased the electricity consumed during the enrichment process, by converting the gas diffusion technology with the centrifugation one, which consumes far less electricity and could explain the lower amount of CO_2 released per kWh. Nuclear power plants dismantling is broken down in three phases: the final shutdown, the dismantling of the reactor building and the other adjacent structures and, at the end, the optimization of waste management. In order to reduce and deal with their radioactivity, liquid and gaseous effluents of the production are treated to absorb the predominant part of toxicity. Before the reactor shut down, the earlier phases are the unloading of fuel and the draining of circuits. Once the shut-off is completed, the disposal of reinforcement steel, concrete, cables and pipes will be pivotal to ensure a safe discharge in the environment.

The spent fuel is either recycled or recovered through the residuals' valorisation, with the final waste accounting for only 4% of the spent fuel. During this process, LCA enables the measurement of potential impacts on the environment, starting from the inventory of materials and energy flows in each different stage in order to avoid double counting and pollution transfers. In the case of the French nuclear power generation, mining represents the main contributing stage, while waste storage is the least contributing stage. The use of coal, natural gas and petrol contributes to the consumption of energy resources during the nuclear life cycle phases. Moreover, water is required for steam production and cooling, however, a distinction must be made between water withdrawal and water consumption. In the EDF life-cycle assessment, direct water consumption is estimated at around 1.3 L/kWh, while withdrawal volumes depend strongly on the cooling system adopted. Overall, EDF nuclear power generation in France produces 3.7 gCO2eq/kWh. This value is significantly lower than the average carbon intensity of the French electricity mix and places nuclear power within the same low-carbon range as hydro, wind and solar generation, while remaining far below fossil-based sources such as natural gas and coal. In this sense, nuclear power has played a central role in keeping the French electricity system among the least carbon-intensive in Europe. However, this climate advantage should not lead to an uncritical assessment of nuclear sustainability, since other life-cycle dimensions including uranium mining, water use, radioactive waste, spent fuel treatment and decommissioning remain essential to evaluate its overall environmental performance (Le-Boulch, D. et al., 2024).

According to the IAEA, two thirds of GHGs emissions are coming from energy production and consumption. At this moment, the deployment of renewable energy sources alone is not enough to satisfy world's energy demand. Furthermore, from 2016 to 2030, global energy supply is likely to double in a way that further compromise and exacerbate alarming climate change related issues. Within this current global energy scenario, nuclear energy could be a relatively environmental ally because of the few CO2eq emissions producing during its entire lifecycle. Diving deeper into the French case, in the period 1960s up until early 2000s, nuclear energy consumption was inversely associated with the emissions level, proving its environmental protection action and sustainability in the long-term. Together with RES, nuclear energy can reduce the emission and improve environmental quality, especially through the implementation of cutting-edge technologies able to diminish the adverse effects of its production. The findings of Bozkaya, S. et al (2025), reveal that a 1% increase in nuclear consumption has a negative

effect on the environment, as it correlates with a 0.30% increase of carbon emissions. Again, the reason could be the lack of investments in new nuclear generation technologies and the too limited production coming from this source to exploit the potential environmental benefits. The drawbacks derive from the problem of indirect carbon emissions generated during building-up, operation and fuel cycle. Overall, it could be useful to compare the cumulative effect on total emissions against the expected positive externalities on the environment, following an increase in the production level. Anyway, the current level of nuclear energy utilization is not sufficient to achieve emission reduction impact alone, given the persistent use of fossil fuels to meet the worldwide energy needs. Despite the main driver of increasing emissions level is represented by the economic growth, nuclear energy contributes to the overall environmental impact throughout its lifecycle. However, nuclear power should be considered as a low-carbon energy source and a valid alternative within a national energy mix. Indeed, the nexus starts from general economic growth and ends with an increase in carbon emissions (Bozkaya, S. et al., 2025).

As we already seen in the discussion, nuclear energy CO_2 intensity is very low if compared to coal, oil, gas and photovoltaic energy sources, while is comparable to wind and biomass alternatives.

Energy source	Wind	Nuclear	Solar PV	Biogas	Natural gas	Oil	Coal
Carbon intensity(gCO2eq/kWh)	12	12	33	49	76	169	185

Table 2.2: Total upstream electricity generation emission factors (Source: IEA, 2025)

In France this is particularly relevant as electricity production mainly comes from nuclear energy. The country strongly relies on its nuclear electricity production and shows a very low impact in per capita CO_2 emissions, accounting for 4.32 tonnes/inhabitant. For that reason, before the treatment phase, the spent fuel will be placed in deposits, like La Hague and Marcoule sites, and only after some decades treated to be definitively stored when the radioactivity will be ceased. However, the process is not the same for long-lived waste, indeed the issue here concerns ensuring its safe confinement within a time span of 100,000 years. Vitrification is the process through which high-level long-lived radioactive waste is

incorporated into molten glass and then cooled into a stable solid matrix, allowing radionuclides to be immobilised before long-term storage or geological disposal. Given the current technological challenge for the implementation of such storage technology, the most feasible solution is the deep geological storage in areas that are not earthquake prone. With an average nuclear fleet age of 40 years, the volume of this type of waste has a storage cost that corresponds to some hundreds of €/MWh. The principal waste residual is plutonium which contributes to the 90% of the long-lived waste radioactivity. A possible solution to reduce its storage environmental and economic impact is offered by fast neutron reactors. This nuclear power plant configuration allows switching from a cradle-to-grave model to a cradle-to-cradle one through the plutonium and depleted uranium re-usage, giving a second life to production waste. In this way, fuel reserves could be multiplied 1,000 times, while it could be possible to reduce the waste to 1/10 of the current volume. The main challenge of using liquid sodium in fast neutron reactors is not primarily technological maturity, but equipment control and operational safety. Indeed, this type of reactor requires liquid sodium in place of water, offering excellent thermal performance. However, unlike the traditional configuration, sodium is opaque, chemically reactive with air and water, and must be kept above its melting point to avoid solidification. These properties complicate inspection, leak detection, maintenance and steam-generator design, making sodium-cooled systems more demanding to operate and monitor despite their advanced technological readiness. The electricity produced through French nuclear power is a proven low-carbon energy source, that consumes few space and resources compared to fossil fuels throughout its lifecycle. It could answer to the growing energy needs of the industrial sector and through its integration with RES, policymakers can massively bring down its environmental footprint (Bréchet, Y., 2020).

According to the research conducted by Lau et al. (2019) regarding 18 OECD countries nuclear energy production between 1995 and 2015, this energy source can be introduced as a low-carbon electricity source that may help reduce the environmental pressure associated with economic growth. Their findings show that in these countries nuclear energy supports the reduction of CO2 emissions without retarding long-run economic growth. Therefore, policymakers should consider this energy source as a valid alternative among their energy and economic policies, also having regard on its mitigating role in the relationship between economic growth and environmental degradation. Indeed, nuclear power is able to generate electricity throughout the hours of the day, while it minimizes GHGs emissions. The results

demonstrate that CO2 emissions are inversely proportionate with the electricity produced through nuclear sources. Even if some studies argue that nuclear could have no impact or a positive one on CO2 emissions, worsening air and environmental quality through its lifecycle phases, it's not questionable how it can serve as substitute for conventional polluting fossil fuels in a first transitory phase, before a complete clean energy transition. Isolating the indirect effect on CO2 emissions produced during construction, operation and end of life of the power plants, the renewable energy generated from nuclear source plays a crucial role in reducing CO2 emissions, otherwise produced by legacy sources. Within this framework, the Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship between economic growth and environmental degradation: at early stages of development, pollution tends to increase with income, while beyond a certain income threshold, further economic growth may contribute to reducing environmental degradation through cleaner technologies, stricter regulation and structural economic change. As electricity production from nuclear is associated with decreasing carbon dioxide emissions, nuclear power can support the transition from the upward to the downward phase of the EKC by providing low-carbon electricity without necessarily constraining long-term economic growth. In addition, in order to contain the adverse effects of global warming, this energy source, has gained a relevant position, given its potential pollution avoidance through the supply of low-carbon electricity. Ensuring an enhancement of environmental quality should be pursued by implementing energy policies that include nuclear energy among the generation mix, while overseeing the potential safety hazards related to radioactive waste management and nuclear installation activities. This confirms that nuclear energy has a strong climate advantage in the electricity generation phase, but its sustainability remains conditional on the safe and responsible management of waste, infrastructure and long-term environmental risks. In conclusion, the authors suggest a balanced interpretation of the data, confirming that nuclear power can reduce carbon emissions in the electricity sector, but its overall sustainability depends on the responsible management of the entire nuclear chain (Lau et al., 2019). The EKC hypothesis is validated if the country's nuclear energy consumption is fundamental to preserve environmental quality. Nevertheless, though nuclear represents a crucial strategy to pursue for energy policymakers, even the most nuclear utilizing countries struggle to achieve environmental protection targets. The implementation of a long-term sustainable energy policy should encompass nuclear and RES to mitigate and reduce CO2 emissions impact. Therefore, the joint rise of these energy sources enables pursuing

a comprehensive energy diversification, with the final aim of maintaining and improving environmental sustainability. Moreover, modern nuclear configurations may have a protective action over the environment, as they foster energy efficiency, after a certain degree of innovation. Some estimates suggest that a reduction of CO_2 emissions by 1% requires an increase of around 3% for nuclear energy, while RES should increase by 5% to produce the same effect. Therefore, phasing-out nuclear could significantly increase the environmental and financial cost of CO_2 emissions reduction. It can be concluded that carbon reduction strategies should include RES and nuclear together to tackle climate emergency because of their negative effect on environmental degradation (Sadiq, M et al., 2023).

Another concerning strictly correlated to lifecycle impact of nuclear energy is represented by water availability for power plants cooling systems. Indeed, high water temperatures could influence nuclear power plants outages and question the overall energy source sustainability. In 2022, many European energy companies experienced challenges in the management of their cooling system due to water scarcity and increased temperatures. Moreover, they had to shut down some of their reactors to comply with environmental regulations that forbid the release of cooling water after a certain temperature threshold to prevent damages on marine and riverine ecosystems. As every unsafe discharge could threaten the resilience of rivers' ecosystem, environmental regulation should limit the impact of warmed cooling water, despite the growing electricity consumption. Allowing a less constrained discharge regime should further exacerbate climate change issue and resulting in biodiversity loss. Furthermore, reaching this environmental tipping point ultimately endangers economic systems due to the strict interdependence between natural and financial capital. In 2021, the whole energy sector consumed around 370 billion cubic meters (bcm) of water, of which 29% utilised by nuclear sector (107 bcm). These figures are expected to increase, indeed by 2030 the total water requirement for the entire energy sector could reach 400 bcm, with nuclear accountable for 32% of the consumption (128,3 bcm). Generally, nuclear power plants consume 35-65 million litres per day, a quantity that could fill 20-25 Olympic swimming pools. However, we must differentiate the amount of water use, that could be used again, from water consumption, where this resource will be no longer at facility's disposal. The unrecoverable water quantity accounts only for 3,7% of the total nuclear energy consumption (4 bcm out of 107 bcm), expected to remain almost unchanged by 2030 (4.8 bcm out of 128.3 bcm). To guarantee a proper functioning of the system, a nuclear power plant requires 50 cubic meters of water per second

to run the operations of a 1,000 MWe reactor. In order to satisfy this water requirement, often environmental landscapes undergo sudden changes with the introduction of artificial dams, tunnels and canals. These modifications enable hydraulic improvements, providing a more stable water volume. Nonetheless, climate change and recent heatwaves could have a negative effect on nuclear power plants' adjacent rivers causing low water levels, increasing the intermittent nature of this energy source and finally questioning its reliability. The European Union set a limit of 3°C maximum increase to avoid severe biodiversity loss and degradation of riverine ecosystems. Nevertheless, this limit is often overcome, generating excessive thermal pollution, as rivers can't bear heating, due to their weak absorption capacity. Nuclear sector claim is the obtainment of some form of exemption from thermal thresholds to avoid electricity generation interruption and the consequent financial criticalities. As nuclear solutions along rivers are becoming unsustainable, seaside nuclear is gaining attention among the possible substitutes. To deal with climate unpredictability, operations vulnerability and prevent financial uncertainties, EDF attempted to restrict water consumption through the development of cooling towers. Unfortunately, despite the resource requirement is restrained, this cooling system configuration raises air and water temperature and worsens environmental quality. In conclusion, cooling system retrofitting doesn't represent a long-term solution useful to reverse this negative trend, as well as investment in nuclear technological breakthroughs doesn't necessarily mean an environmental improvement, if not complemented by the diversification of energy sources (Gutting, A. et al., 2025).

2.2 LCOE of nuclear vs alternatives

Throughout the years, EDF sharply updated its accounting method, by switching from a budgetary approach to IFRS (International Financial Reporting Standards) norms and the French accountability system. Through the exploration of historical documents that recorded expenses related to first building phases of nuclear energy fleet, EDF has esteemed an initial nuclear construction cost that accounts for 72.9 billion $€_{2010}$. Even though the evolution from one approach to another has surely affected the expenditure assessment, this figure represents the most reliable esteem of the historical French nuclear fleet initial expenditure. Moreover, the cost for every MW of installed capacity had suffered a progressive rise in the years, especially because of the application of stricter regulation. As the preliminary building stages required a notable initial capital expenditure, the joint effort aimed at the obtainment of scale economies

among different nuclear installations. However, despite this cost reduction attempt, the nuclear average cost was 1.17 million €$_{2010}$/MW. The initial investment overnight cost was necessary to develop the current French nuclear fleet. Among its components, one should include the construction costs, the engineering and workforce charges, together with the pre-exploitation expenses. The sum of these cost items leads to an amount of around 83.2 billion €$_{2010,}$ though the accuracy of the numbers is somewhat debatable, depending on the cost structure choice. The net book value of the national nuclear fleet in 2010 corresponded to 17.9 billion € based on EDF calculations or 18 billion € through the application of IFRS norms, highlighting the two estimates matching. This weak value resulted from the deduction of depreciation from the gross value of nuclear installations. Even if, the original depreciation system planned declining-balance depreciation over 30 years, recent adjustments introduced extensions to 40 years given the potential life extensions through LTO interventions. Long before the final electricity generation step, a nuclear power plant facility requires construction cost coverage, without earning from not yet started production activity. IFRS norms allowed EDF to capitalise interest costs to finance monetary outflows during building process. This accounting rule enables the recognition of interest charges as part of the starting investment. Through the isolation of inflation effect and the utilisation of a 4.5% adjusted rate, the maturity value is 12.78 billion €$_{2010}$. The exploitation of the current nuclear energy capacity has been preceded by extended research on reactors, fuel cycle, safety and security of applications. During the period 1957-1969, civil nuclear research investments hit 14.4 billion €$_{2010,}$ equal to a 1.1 billion €$_{2010}$ yearly average. In further detail, 11.2 billion €$_{2010}$ of the research funds were dedicated to the first two generations reactors and the fuel cycle development (about 78% of the total investments), while the remaining 3.2 billion €$_{2010}$ allocated to FBRs enhancements. It is fundamental to highlight that 10.7 billion €$_{2010}$ were spent by CEA, which during those years was actively engaged in the fabrication of the nuclear bomb. Then, the research expenses yearly average reached 1 billion €$_{2010}$ in the period 1970-1989 and 1.2 billion €$_{2010}$ between 1990 and 2002. Regardless of the time framing, the entire applied nuclear electricity research of the period 1957-2010 has reached 55 billion €$_{2010,}$ translated in a 1 billion €$_{2010}$ yearly average. Suffice it to say that Superphénix expenditures have been 12 billion €$_{2010}$ in the period 1974-1997. In every case, despite the impressive amount invested, this case should be assessed with a two-fold industrial and research status, given the frequent operational changes undergone. At the end, the total past investments aimed at nuclear electricity production that enabled the current fleet realisation is 188 billion

€$_{2010.}$ The physical investment part constitutes 64% of the global expenditure, while applied research and Superphénix project alone accounted respectively for 30% and 6%. Moving to the fuel cost, one should consider two cost items. The first is represented by the Orano (former AREVA) fuel supply utilised for nuclear power plants cycles. The other component is the fuel waste management cost incurred due to uranium and plutonium spent fuel. The average total generation cost of the current fleet is evaluated at 60.3 €/MWh with fuel consumption responsible of most of the yearly variable cost. Therefore, as fuel cycle weight corresponds to 10-15% of operational cost, fuel expense is between 6 and 9 €/MWh. Among the external consumptions other than fuel, nuclear power plants require ordinary and extraordinary maintenance. Often these expenses are under subcontracting law regime, and they can't be considered as part of EDF fixed assets. The national electricity company bears the taxes and fees payment that will be part of the nuclear electricity production cost and then applied on the customer's bills as component of the final electricity price. Specifically, there are an excise duty proportional to consumption in kWh, a fixed component related to transmission and distribution and the VAT at 20% on the subscription. The distinction underlines how the final retail price of electricity does not simply reflect the cost of nuclear generation, but even taxation, network tariffs and public-policy charges. The aggregated exploitation cost associated to nuclear electricity production in 2010 was equal to 8.9 billion €, also expressible in 22 €/MWh. By way of comparison, in 2025 the total exploitation cost has been 35.2 €/MWh, while the entire cost of production envisaged for 2026-2028 is 60.3 €/MWh. In 2010, waste management gross cost for EDF spent fuel has been declared to be 14.386 billion €$_{2010.}$ The cost components included transport, storage and vitrification of spent fuel and reprocessing residuals. In 2025, the global spent fuel cost reached 17.449 billion €, highlighting an expenditure rise of 18%, compared to 2010 level and excluding the inflation effect. To complete the picture, it is pivotal to assess the economic impact of CEA spent fuel management. In 2010, the sum of the fuel cycle waste charges was equal to 419.9 million €$_{2010,}$ while this figure has reached the actualised value of 790.4 million € in 2025. Moreover, the waste management cost to bear for High-Level Waste (HLW) and Intermediate-Level-Long-Lived-Waste was around 22 billion €$_{2010}$ (Cour de Comptes, 2012). According to French nuclear agencies most recent data, this amount is nowadays equal to 33.3 billion € for *Cigéo* geological disposal construction, excluding project specific taxation. Given the nuclear energy exploitation of water sources, air quality worsening and natural landscape modification, it is fundamental to assess the economic impact of these

negative externalities. Starting from the French nuclear energy life cycle assessment previously conducted, this energy source generates 3.7 gCO_2eq/kWh. The multiplication of this number with the total electricity generation from nuclear energy (373 TWh in 2025) gives the result of 1.38 million tonnes of CO2 equivalent emissions. Then, depending on the reference benchmark choice, it is possible to perform the economic evaluation of the carbon dioxide emitted. Assuming a value of 86-87 € for each CO_2 tonne, aligned with the European Union Allowances (EUA) traded in the EU ETS market, the monetisation of the climate negative externality gives the value of approximately EUR 119-120 million. Accordingly, this CO_2 pricing will give an external climate cost of only 0.32 €/MWh, consolidating the few negative externality produced by nuclear compared to its overall generation cost.

In this attempt to give the best economic assessment of nuclear advantages and disadvantages, the Levelized Cost of Electricity (LCOE) serves to assess the cost of a specific technology, allowing comparisons between different baseload solutions. In a simpler way, one could approach this method by comparing it with the calculation of the electricity production cost within regulated markets characterised by stable tariffs. Its final value corresponds to the minimum selling price of electricity produced through a specific energy source, expressed in monetary terms. The parameter suggests the break-even selling price necessary to cover capital expenditures, interests and debt obligations repayments, on top of a fair market return for investors. Nonetheless, in the current electricity markets' scenario choosing the technology with the lowest LCOE value doesn't always represents the best possible solution. Because of fuel price costs, technological maturity availability of sites, the costs for all technologies can be very different, depending on country and region. In Europe onshore and offshore wind and solar installations are competitive compared to gas and new nuclear energy. Conversely, RES bear higher costs than fossil fuels or nuclear-based generation in countries like Japan, Korea and Russia. In the United States, gas-fired power plants benefit from low fuel price condition, anyway onshore wind and utility scale solar PV represent the least cost options. In China and India, nuclear energy is competitive, but the variable renewables have the lowest generation cost in both countries, demonstrating a possible pursuable transition pathway. As a result of both demand and supply side structural changes, storage advent and growing flexibility requirement, often an energy sources portfolio broad evaluation is more relevant than the assessment of a single production unit outcome. LCOE of low-carbon technologies is becoming more cost competitive, showing that its costs are below the ones of fossil fuels generation.

Renewable energy cost is competitive compared with the conventional energy sources, with emissions that account only for USD 30/tCO2. Even hydro technologies are reliable alternatives in terms of expected lifecycle costs, even if they suffer sites' specificities. Nuclear energy, as well-established low-carbon dispatchable technology, bears the lowest expected cost among the other exploitable energy sources. Indeed, nuclear power plants cost projections show that this technology can become more cost-effective than Combined-Cycle Gas Turbines (CCGTs) and more affordable than coal-fired plants. A lifetime extension of existing nuclear plants facilities represents a cost-effective solution to restore secure operations. The renewal and refurbishment of the existing infrastructures enables cost savings, not otherwise obtainable through investments in new sites. The estimates show that the retrofitting of incumbent infrastructures allows the achievement of the same capacity factor that would have been obtained with the start-up of new sites. Moreover, the effect of long-term operation (LTO) expansion on nuclear power plants' LCOE is particularly visible when the extension goes beyond 10 years, and it's maximised at 20 years' time periods. Analysing the median investment required for a LTO extension of 10 years the value for a French nuclear plant at 85% capacity factor is 12.45 USD/MWh, while a 20 years LTO extension would require 8.25 USD/MWh, thus demonstrating a 34% higher monetary effort in the nearest scenario (10 years). It's important to bear in mind that the result is especially relevant in France, as this assessment is country-specific and depends also on the discount rate choice (7% in this example). Controlling for the other conditions, with a discount rate of 3% the 10-year scenario is 43% more expensive than the 20 years one, while when discounting at 10% make the investment 28% costly. The cost-effectiveness of a retrofitting measure is further justified by the investment cost required by decommissioning process, which is around 35 USD/MWh in the specific case of French nuclear power plants. Browsing the renewable alternatives, French solar capital investment required would be 30.17 USD/MWh for a utility-scale PV installation, while it would be 49.26 for commercial users and 98.51 for residential ones, all considering a 7% discount rate. Conversely, the cost of decommission for this renewable solution would reach around 75 USD/MWh. Onshore wind (>= 1 MW) investment with the same discounting assumption, would necessitate a 38.04 USD/MWh financial effort, whereas its decommissioning would cost 56.08/MWh. Differently, offshore wind with a net capacity of 500 MWe would demand 66.81 USD/MWh resources of investments. Eventually, France storage technologies include fuel cells which depending on their net capacity (MWe) would require an investment range between 29

USD/MWh and 82 USD/MWh. A lifetime extension for LTO beyond 40 years would require an additional capacity of up to 20 GW to consolidate the expected decarbonisation efforts.

The issue of high expenditures required for new nuclear plants is particularly relevant in countries with few nuclear previous construction experience, while it's absent in countries with well-established supply chains that have continuously invested in nuclear power plants during the years. Moreover, despite the projected cost of new nuclear projects was above 5000 USD_{2018}/kWe in 2010, the trend for the 2025-2030 overnight costs is 4000 USD_{2018}/kWe, corresponding to a 20% cost reduction. However, to reduce both system and plant-level costs, the energy policymakers may pursue different strategies including LTO of existing nuclear assets, cost reduction in new generation reactors and technology innovation through SMRs. In the recent years, OECD countries have experienced a significant cost increase, especially in the period 2010-2015, further exacerbated by important construction delays. In France, the Flamanville 3 unit has exceeded by three times its planned construction time, while suffering a rise in the annual construction cost from 1,886 USD/kWe to 8,620 kWe. At global level, this uncertain framework increased the perceived risk, by hindering the investment opportunities. An overnight cost reduction of 20% to 30% could be achieved through the implementation of a more standardised and efficient reactor design, that in its turn would reduce the level of riskiness. Once obtained the designed maturity, the effective project management and the regulation predictability will enable a faster replicability, through the exploitation of series effects.

The final output of LCOE calculation is a stable electricity tariff (Price at MWh) that encompass the whole project lifecycle. This value represents the constant remuneration given to the electricity supplier.

$$LCOE = PMWh = \sum (Capitalt + O\&Mt + Fuelt + Carbont + Dt) * (1+r)\text{-}t \,/ \sum MWh\ (1+r)\text{-}t$$

The formula includes the capital expenditure for the investment, operation and maintenance, fuel, carbon emissions, decommissioning and dismantling. To better understand the expected value generation, this figure is discounted, making it more appropriate for a heterogeneous stakeholder's panel formed by investors, owners and operators. The discount rate is a key determinant of competitiveness, as it reflects the opportunity cost of a possible investment by considering multiple risks and uncertainties. By way of illustration, the LCOE discount rate of new nuclear plants is 3%, comparatively low than the ones of new coal and gas plants. However,

if the nuclear discount rate would rise to 7% or 10%, this would mean an increased risk that would discourage investors as this rate would exceed the one of fossil fuel-based plants (IEA et al., 2020).

According to Boccard, N. (2014), French nuclear electricity historical cost is between 59 and 83 €/MWh, at 2010 prices. The first estimate corresponds to the best-case scenario, while the higher estimate is more prudent and conservative, especially having regard on future liabilities, capital remuneration, accident insurance, waste management and decommissioning. This cost range suggests that the French nuclear fleet has produced electricity at a cost broadly comparable with European market prices. The French nuclear model advantage during the building phase was the standardisation and industrial coordination, that helped contain capital cost escalation compared with the United States. Nevertheless, this advantage was partly offset by operational weaknesses. The French fleet displayed a relatively low-capacity factor, around 76%, meaning that a significant share of installed nuclear capacity was unavailable or not producing electricity at full potential. As LCOE depends strongly on the amount of electricity generated over the plant lifetime, the lower availability positively influenced the cost per MWh. Furthermore, operation and maintenance costs appear unusually high in the French case, making the economics of nuclear power less favourable than a simple capital-cost comparison would suggest. This comprehensive accounting framework is particularly relevant for nuclear energy, because a significant part of its costs occurs either before commercial operation, through capital investment and development, or after electricity generation, through dismantling and radioactive waste management.

Energy source	LCOE
Historical French nuclear	59-83 €/MWh
Coal	52 $/MWh
Natural gas	64 $/MWh
Wind power	78 €/MWh

Table 2.3: LCOE historical comparison between French nuclear and other energy sources (Source: Court des Comptes, 2012)

These findings demonstrate the competitiveness of historical French nuclear power, even highlighting its questionable affordability compared with other energy sources. Indeed, coal-fired electricity appears cheaper in the absence of a carbon price, while natural gas is presented as flexible and relatively low-cost, although highly sensitive to fuel-price volatility. Conversely,

wind power has a low-carbon profile comparable to nuclear power and appears economically competitive with future nuclear projects, especially in Europe. The main difference is that nuclear power provides dispatchable baseload electricity, whereas wind power is intermittent and requires system-level integration. Therefore, the comparison cannot be reduced to LCOE alone, but LCOE still shows that new nuclear power faces a more difficult economic position than the historical French fleet (Boccard, N., 2014). The economic competitiveness of a specific energy source should be evaluated besides the broader environmental policies framework. Indeed, the absence of environmental thresholds on carbon emissions and environmental hazards, fossil fuels would gain relevance and would be chosen as the most favourable options. At once, unpredictable or unrealistic energy policies could encourage the development of energy solutions that offer higher remuneration rates and more stable risk profile. As the electricity generation cost is heavily influenced by the cost of capital, nuclear energy suffers elevate overnight cost and extended building time. Together with policymakers' unfavourable policies and the unstable regulation, even social acceptance could worsen nuclear investments riskiness. A method to reduce the probability of these plants' life-cycle events may be the structuring of financial operations in order to support the transposition of risks. Furthermore, electricity markets dynamics allow a reduced exposure to electricity price volatility through financial instruments like forward contracts, futures and power options that streamline plants' operations management. The huge capital availability requirement shed light on French state involvement within nuclear energy program. This sector industrial development benefited from low financing risk and better standardisation of facilities, as result of state's meddling. (Mari, C., 2014).

The LCOE is commonly employed for the assessment of economic performance of electricity-generation technologies. It is calculated by comparing the discounted stream of all costs incurred over the lifetime of a plant with the discounted amount of electricity produced during the same period. In the nuclear case, this methodology is particularly relevant because costs are distributed across several stages of the nuclear fuel cycle, including uranium supply, conversion, enrichment, fuel fabrication, reactor construction, operation and maintenance, spent fuel management, interim storage and final disposal. The LCOE evaluation method can be extended to the different nuclear fuel cycle configurations. The first is the traditional Once-Through cycle, in which spent fuel is sent for disposal and without recycling possibility. Instead, the Twice-Through cycle allows a second pass for plutonium and a part of uranium

obtained from the ended cycle, while a Fast Reactor Recycle System enables a repeated recycling of plutonium and the minor actinides. According to De Roo, G. et al. (2011), through the enforcement of the traditional LCOE methodology, one can investigate each reactor or fuel design separately, given the wide nuclear setting opportunities. However, the researchers argue that fuel cycle cost calculations should be integrated together with the assessment of the other nuclear life cycle costs. The application of such approach prevents an artificial separation between reactor costs and fuel-cycle costs, showing that the economic assessment of nuclear power must include both front-end costs, such as uranium supply and fuel fabrication, and back-end costs, such as spent fuel treatment, storage and disposal (De Roo, G. et al., 2011).

2.3 Analysis of kWh cost

This section aim is to analyse the evolution of electricity prices for a selected panel of European countries in the period 2007-2025. The expected results are obtained using Eurostat electricity price data as primary data source. For the relevance of this thesis breakdown, this part encompasses a comparison of major European countries domestic energy price, as well as of the EU27 average, with the French specific case. These data provide a harmonised overview of both household and non-household electricity prices from 2007 onwards. The following figures constitute the final retail prices and include network charges, taxes, levies and VAT. European Commission indicates that in Europe retail price is obtained through the interaction of wholesale energy costs and the other components mentioned above. The difference in EU nations' electricity prices is justifiable by countries specific taxation, grid costs, market design and fossil fuel prices volatility. Within this framework, one should investigate the role of nuclear power and its share in the electricity mix to understand a possible correlation between this energy source and wholesale prices. However, nuclear share alone could not explain all price fluctuations, without controlling for taxes and levies, system charges and national electricity market features. Taking in reference 2015-2019 period, EU wholesale electricity price has swung between 40 and 60 €/MWh, while spot prices remained stable in 2018 and started to decrease the year later because of a weakened demand, more convenient fuel costs and renewable electricity injection rise. In 2020, Covid-19 pandemic consequences generated a drop in electricity demand, that then resulted in negative intra-day prices and wholesale downward values with a low bound of 17 €/MWh. European electricity market suffered an intense disruption initially provoked by Russian interference with gas supply, then exacerbated

into Ukraine invasion. This geopolitical tension fostered a steep rise in EU wholesale electricity prices, since higher gas prices led to more expensive supplies other than Russia. The reason behind this price surge is that gas-fired power stations within Europe set the wholesale electricity price. Moreover, the absence of cheaper power generations source, along with RES intermittence and multiple nuclear outages further worsened the situation. As a result, EU electricity prices reached the record level of 400 €/MWh in August 2022. Despite the 2022 anomalies, since the end of that year, the average electricity prices are back between the range of 70 and 120 €/MWh. The rapid evolution and restoration of the pre-pandemic level has been achieved through a shrinking demand, higher RES and nuclear availability and a general negative trend in gas prices. Before the energy crisis, European electricity prices were more competitive with the ones recorded in Asia, even if historically higher than US levels. Increased gas prices and Russia-Ukraine conflict pushed EU electricity market towards a close alignment with Asia and made the union average between 2-5 times higher than US prices. Wholesale prices reflect the market price of electricity before it reaches final consumers, while retail prices correspond to the final price paid in the bill, including energy costs, network charges, taxes and levies. In the period 2010-2019, retail electricity prices have been relatively stable and above wholesale ones. They suffered a rapid increase in 2021 as a direct consequence of wholesale electricity prices rising. Nonetheless, during the energy crisis, wholesale prices growth led to exceptional peaks that, from late 2021 onwards, temporarily exceeded retail prices. This mechanism demonstrates how wholesale prices react more immediately to market shocks, while retail prices adjust with a delay due to regulation, contracts and policy interventions. Concretely, EU27 average retail electricity price augmented from 235 €/MWh in 2020 to 371 €/MWh in the second half of 2022, with peaks above 500 €/MWh throughout Europe. Moving to the European households' energy expenditure, in the recent years it has been characterized by a negative trend, especially from 2012 to mid-2021, until the energy crisis outbreak. The consumers final cost is determined by the combination of retail prices and user's effective consumption. Therefore, in 2021 and 2022, rising energy prices affected European households' energy spending, with many consumers struggling to satisfy their energy demand due to excessive costs. This series of adverse events impacted EU economy through a considerable increase in the union's fossil fuel import bill. Indeed the 2021-2022 crisis has caused a long-lasting change in the European gas supply, bringing LNG (liquified natural gas) to approximately 40% of gas imports share. (European Commission, 2024)

On this basis, the following graphical section provides a descriptive comparison of electricity price trends across selected European countries and the EU27 average. The data is extracted from Eurostat and processed through RStudio to allow for countries' visual assessments. Particularly, the final aim will be to frame France's position within the broader European electricity price landscape, providing in this way the basis for discussing the expected relationship between nuclear reliance and final electricity prices.

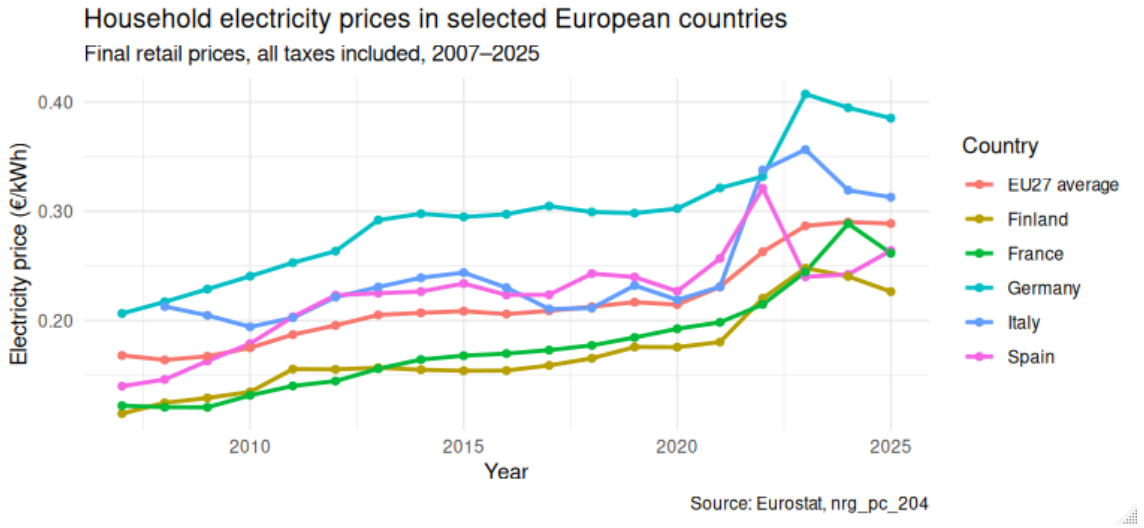


Figure 2.1: Evolution of EU households' electricity prices

This figure pinpoints the general upward trend of households' electricity price for the selected countries, shedding light on the sharp increase experienced during the years 2021-2022. More precisely, Germany and Italy presented higher retail prices compared with EU27 average, while France remained close or below the union pathway and still less than 0.30 €/kWh. Spain prices evolution differed from the previous ones, though steadily aligned with European average, while Finland has the lowest household price value for the selected period.

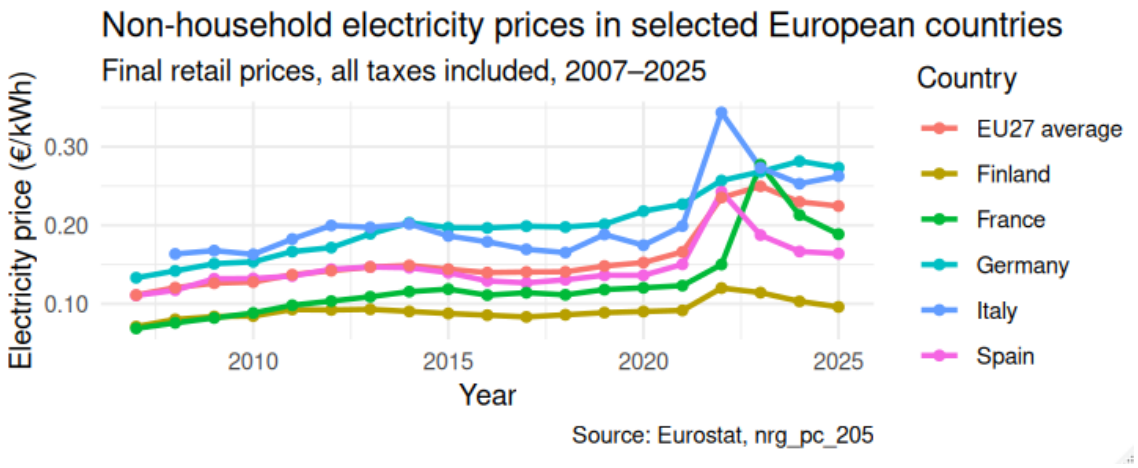


Figure 2.2: Evolution of EU non-household electricity prices

The graph shows the non-household electricity prices dynamics for the indicated time span, and it is useful to visualize French price trajectory in comparison with our panel. Generally, France positioned below EU27 average (see Figure 2.3) and the selected panel of countries, excluding Finland which presented the most competitive European industrial electricity tariffs. As previously predicted, energy crisis has impacted on all EU national industries, though with their specific recovery routes.

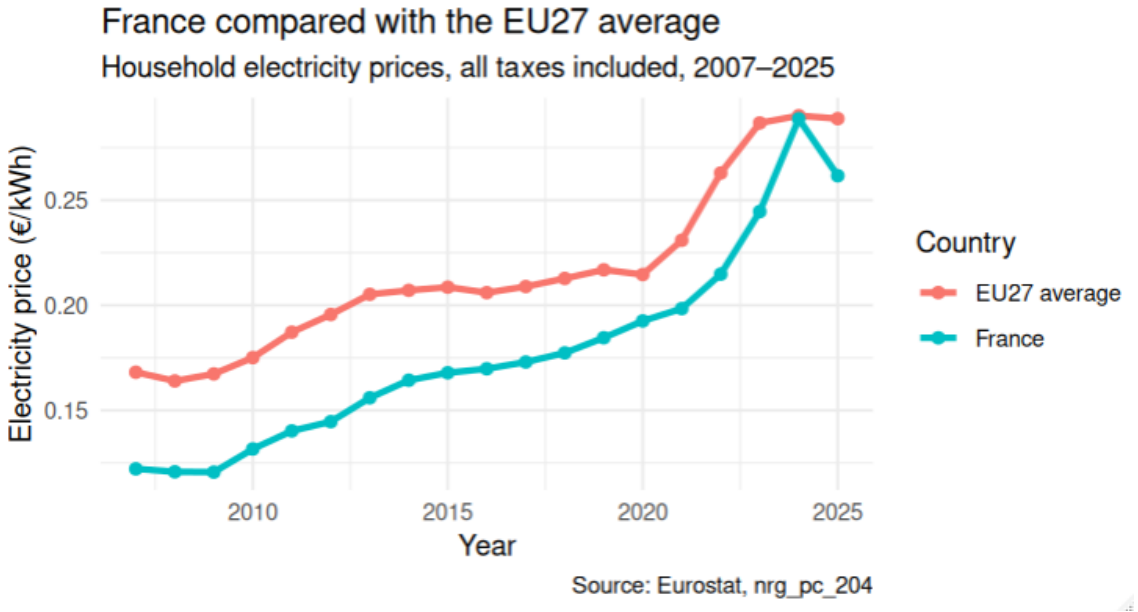


Figure 2.3: French vs EU27 average household electricity prices

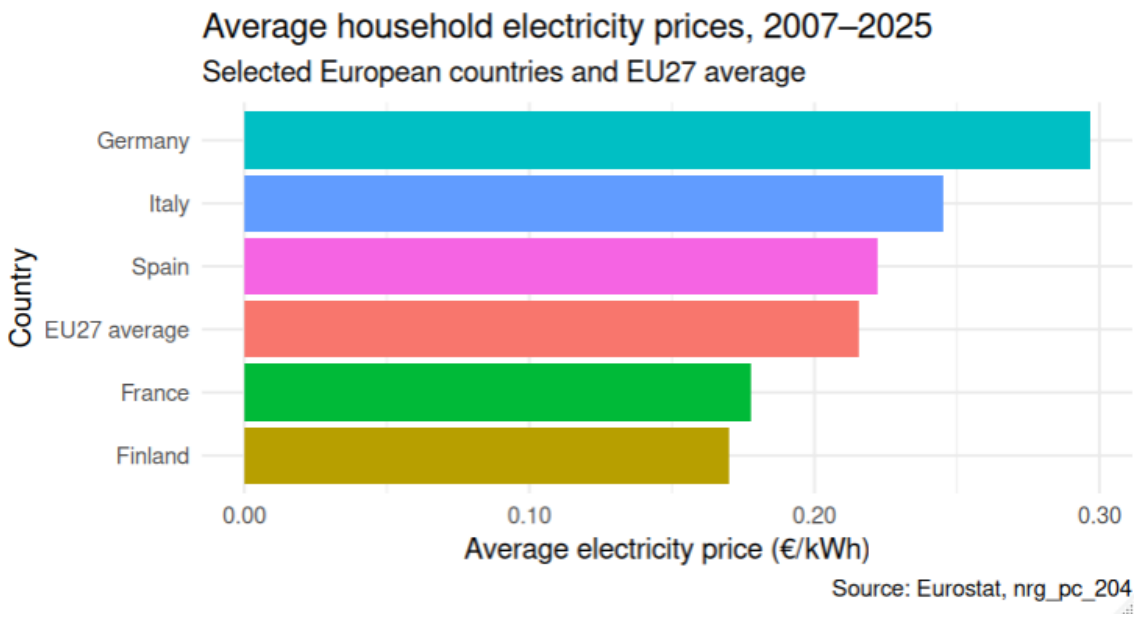


Figure 2.4: Summary of average household electricity prices within European selected countries

The average households' electricity price comparison shows that Finland and France have provided the most competitive energy tariffs during the period of study, settling on a 0.17 €/kWh average price. This can be partly explained by their nuclear quote within their energy mix that have significantly reduced their reliance on fossil-fuel price volatility. By contrast, Germany, Italy and Spain have borne higher average prices due to their specific energy markets' conditions. Germany phased out its nuclear electricity production and suffered heavy network costs and market restructuring. The country recorded an average price of around 0.29 €/kWh, approximately 70% higher than France and Finland, which stood around 0.17 €/kWh. Spain and Italy presented very similar averages, 0.22 €/kWh for the first and 0.24 for the latter, slightly above the EU27 average due to strong dependence on gas-fired marginal pricing, taxes and complex regulations.

The exploration of the questioned relationship between nuclear reliance and electricity prices is performed through the combined analysis of Eurostat electricity price data with annual nuclear electricity shares from Our World in Data/Ember. The nuclear share is defined as the percentage of total national electricity generation produced by nuclear power. The analysis is carried out for France, Finland, Germany, Italy and Spain over the period 2007–2025. The correlation analysis is descriptive and should not be interpreted as evidence of causality. Indeed, final retail electricity prices include network charges, taxes, levies and regulatory components,

while wholesale prices are also affected by gas prices, market design, renewable availability and temporary supply constraints. Therefore, a negative correlation between nuclear share and electricity prices would suggest an association between nuclear reliance and more contained electricity prices, but it would not prove that nuclear power alone directly causes lower prices. A negative correlation would support the hypothesis that countries with a higher nuclear share, such as France and Finland, tend to display lower or more moderate electricity prices compared to the others. Otherwise, a positive correlation near to 1 would suggest that a greater nuclear energy share implies electricity prices increase, while a null value highlights a not clear relationship (Italy's case). However, the result must be interpreted as a preliminary descriptive indication, since taxation, grid costs, fossil-fuel exposure and national market structures remain important determinants of final electricity prices.

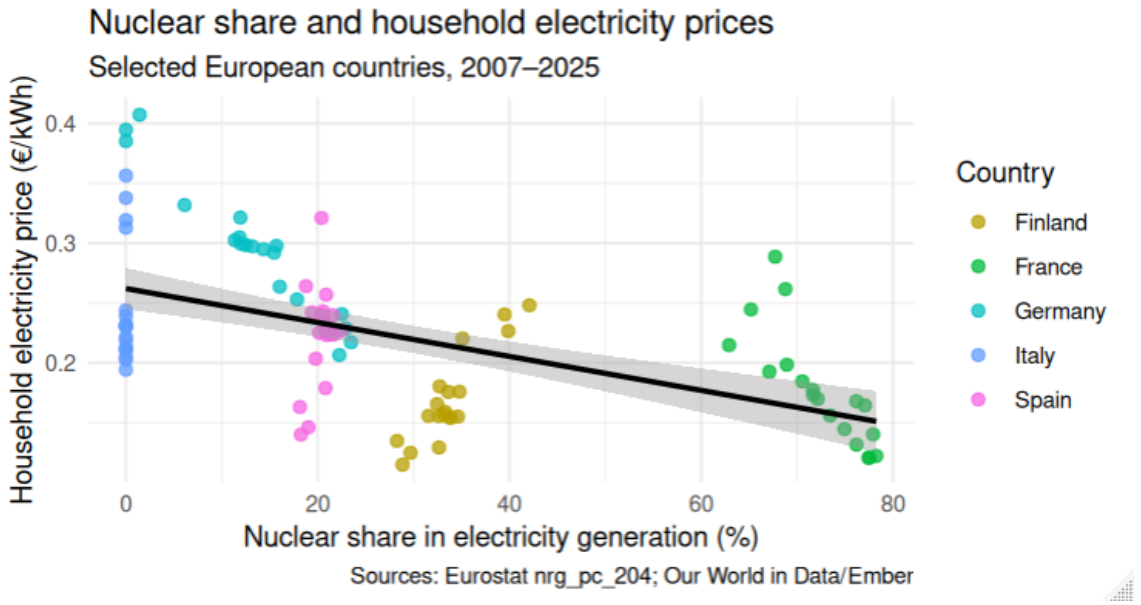


Figure 2.5: Correlation between household electricity price and nuclear share in electricity generation

The scatter plot explores the relationship between the nuclear share in electricity generation and household electricity prices in selected European countries between 2007 and 2025. According to the figures, the fitted regression line suggests a negative association: countries and years with a higher nuclear share tend to be associated with lower household electricity prices. The correlation coefficient of r = -0,54 suggests a moderate negative association between nuclear share and household electricity prices. This pattern is particularly evident in the French case, where the nuclear share has always been very high, generally between around 65% and 80%,

while household electricity prices have been comparatively moderate for most of study time span. France pathway therefore appears consistent with the hypothesis of high nuclear share contribution to more contained electricity prices, especially through the reduction of fossil-fuel price volatility exposure. Finland also supports this interpretation to some extent, as it combines a relevant nuclear share with relatively low household prices. Conversely, Italy shows a correlation equal to zero, as the country has no domestic nuclear generation, while Germany, whose nuclear share has declined over the period and eventually phased out, is positioned in the higher-price area of the graph. Spain is placed in an intermediate position, with a moderate nuclear share and prices that remain closer to the middle of the sample. Nevertheless, this relationship should not be interpreted as proof that nuclear power directly causes lower electricity prices. This because final household retail price includes not only generation charges, but even network charges, taxes, levies and VAT. Moreover, electricity prices are influenced by several additional factors, including gas prices, market design, RES integration, interconnections, national regulation and crisis-related policy interventions. Lastly, the observed negative correlation should be understood as a descriptive indication that nuclear power may contribute to price moderation when it is part of a broader low-carbon and less fossil-dependent electricity system.

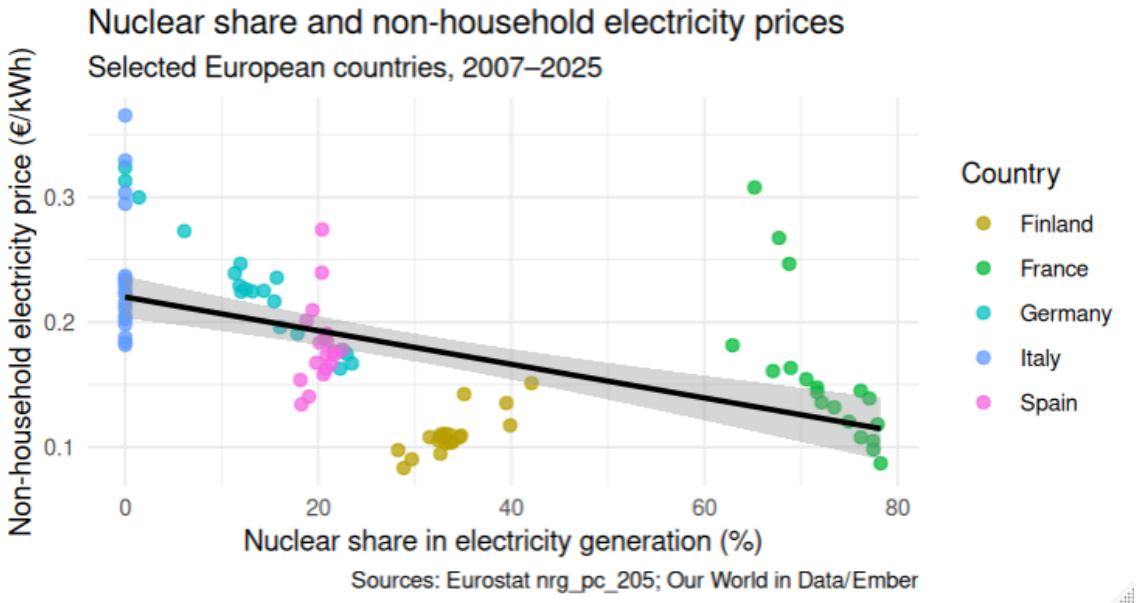


Figure 2.6: Correlation between non-household electricity price and nuclear share in electricity generation

The non-household correlation value of –0.53 is very close with the household case (-0.54). This result is relevant for industrial and business consumers, as electricity prices directly affect enterprises' competitiveness, constituting an important operational cost. Not surprisingly, Finland and France are positioned in the lower price area, and both rely on a significant nuclear component for their electricity production purposes, while again Italy and Germany occupy the higher prices positions within the chart. This may indicate that nuclear power contributes to industrial price competitiveness by limiting exposure to fossil-fuel volatility, enabling the offering of cheaper national electricity. Nevertheless, the relationship remains descriptive rather than causal, as final prices also depend on taxes, network costs and market design, even in this case.

The analysis also encompasses an assessment of nuclear share with tax-excluded electricity prices. This step is useful to make the study more homogeneous the panel of study, as final retail prices include fiscal and regulatory components that differ significantly across countries. The removal of taxes and levies allows an analysis more focused to the energy-cost component of electricity prices, although it still does not represent a pure generation cost or LCOE. If the negative relationship between nuclear share and electricity prices is persistent even excluding tax components, this would strengthen the descriptive hypothesis that nuclear power may be a price moderator, ensuring lower exposure to fossil-fuel price volatility.

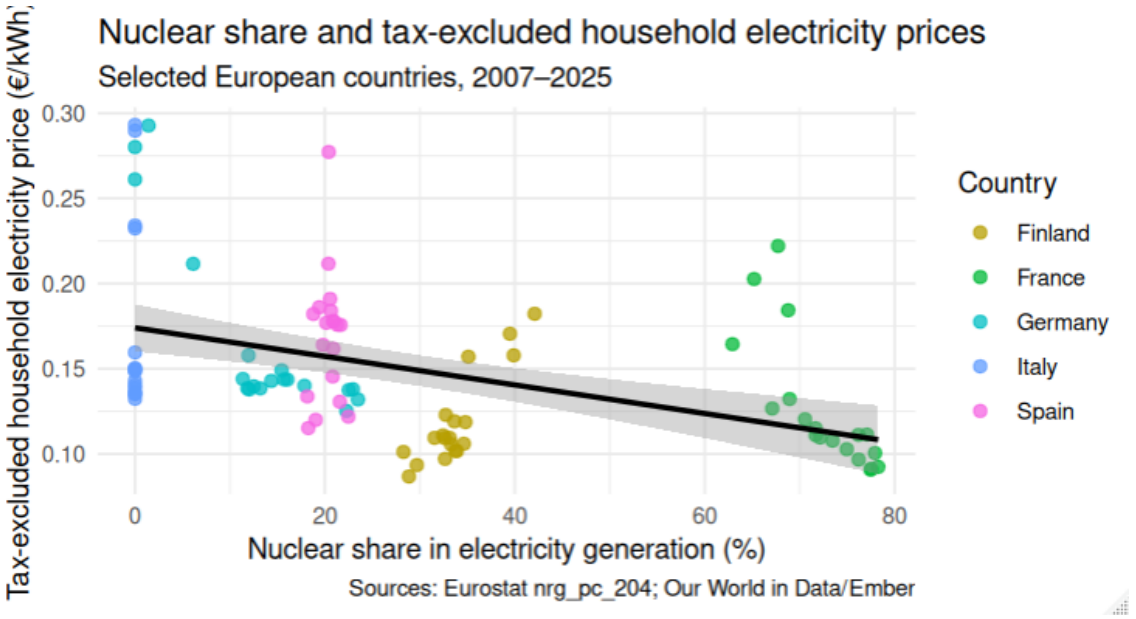


Figure 2.7: Correlation between nuclear share and tax-excluded household electricity prices

As previously expected, the correlation between nuclear energy presence in the energy mix and electricity prices without taxes applied is –0.43, suggesting a limited negative association. Although the negative trajectory is still visible, this correlation is weaker than the one based on final retail prices (see Figure 2.5). Therefore, the association between higher nuclear share and lower retail prices cannot be justifiable only by different taxation levels and the relationship is not uniform across all countries. Indeed, observing Finnish higher nuclear share, one can see a slight increase of tax-excluded electricity price, contradicting the expected pattern. Again, this gives proof of countries' specificities influence on the general results, even after excluding taxes. On the other hand, the French case respects the predicted direction more consistently, making more visible an association between nuclear presence and low tax-excluded prices. To complete the overall picture, Italy and Germany null and/or declining nuclear shares correspond to upper bounds of kWh prices. In conclusion, those interconnections assessment should be read as a pooled descriptive correlation, which brings together countries-level time series observations. This study has partially confirmed the hypothesis of nuclear energy production as driver of moderate electricity prices, particularly in the French case. However, nuclear power by itself does not reflect all price dynamics, even after exclusion of taxes. This economic analysis cautiously suggests that in presence of nuclear energy a country could obtain more stable electricity prices. Anyway, this effect must be framed within a wider electricity system, that is largely influenced by fossil-fuel exposure, network costs and RES availability. Further research could deepen this relationship by introducing more specific control variables, such as fossil-fuel dependence, gas prices, network charges, renewable penetration, import dependence and country-specific regulatory frameworks.

III. The French nuclear energy pathway

3.1 Historical phases and turning points

Following Vaïsse's distinction between chronological and thematic approaches to the historiography of French nuclear power, this section adopts a chronological perspective with the aim to identify the key historical turning points of the French nuclear programme. This approach streamlines the following of nuclear policies evolution over time, while at the same time it also highlights recurrent themes such as energy security, independence from oil imports, environmental risks, centralized decision-making and the dominant role of the French state in the nuclear sector (Vaïsse, M., 2011). The transformation of nuclear energy sector from a primordial and experimental sector into a highly organised national industrial system represented the major turning point in the history of French nuclear power. From the 1950s onwards, the country's nuclear programme was carried out through the interaction between State, the CEA, EDF, major industrial suppliers and, progressively, nuclear safety institutions. This setting enabled the creation of a hybrid model, both public and private, monopolistic in France but extremely competitive abroad during the years (Torres, F., 2018). The current nuclear fleet was developed by the key actors just mentioned, that still nowadays, sometimes with new acronyms and operative structures, perform pivotal roles within nuclear energy operations. Électricité de France (EDF) is the national electricity utility monopoly from 1946, when it was decided the nationalisation of several small companies to avoid competition and benefit from state aids through an integrated monopoly configuration. This system does not encourage market competition, unlike in US and UK where the coexistence of many electricity utilities is admitted under law. Indeed, French government owns 100% of the society since June 2023, with the delisting and withdrawal from Paris Stock Exchange (EDF, 2023). Areva was the main nuclear engineering firm and one of the major actors in the nuclear industry. The company was unbundled in divisions that were responsible of construction of nuclear reactors and the fuel cycle management, including the reprocessing of spent fuel and waste management. The company operated in this field since the construction of the first recycling facility in La Hague in 1966. The *Commissariat à l'énergie atomique et aux énergies alternatives* (CEA-Atomic Energy Committee) holds a prominent role in the French nuclear sector. The institution came to life in 1945 to conduct nuclear research for national defence interests and even today gives is contribution in military and civil nuclear R&D. The institution creation by De Gaulle represented the beginning of France's political interest over nuclear energy. The French

technocracy ensured the coordination of these main actors involved in nuclear management and planning. The techno-power was very favourable for atom purposes as the executive leaders of these three main organisations had studied at Ecole des Mines, a prestigious university that provided them with the same level of efficiency. Therefore, the political *grand programmes* have been launched without public opinion opposition, thanks to the efficiency driver that characterised both left and right wings of the Parliament during that period. Inevitably, nuclear power gained strong consensus and acceleration, facilitated by the vertical integration of the nuclear value chain, entirely controlled by these few institutions (Stuart, C., 2017). In 1954 Guillaumat was the responsible for the French nuclear program, while Mendès-France was the Prime Minister. The politician was the decider who had to choose among the options proposed by the expert. The nuclear plant was a technical device, however through its exploitation, policymakers could decide whether generate electricity while producing the bomb or convert it entirely to electricity production. This example of relation between science and politics brings out the origin of the civilian-military link concerning the use of nuclear as public good and public defense instrument. Nuclear energy was politicized by EDF through its economisation and the application of the indisputable kWh cost criteria to strengthen its legitimacy. The concept of public service, prompted by this political choice, guaranteed energy supply quality, together with equal market tariffs under the equity principle and the cheaper price offering. The early French nuclear programme was deeply connected to the post-war reconstruction of national prestige. Nuclear technology became a way to restore the *grandeur* of France through the continuous implementation of scientific achievement, industrial modernisation and national power. French nuclear power was not only a mere technological energy solution, rather it represented a symbolic joint engagement between different actors who projected the country's modernity, sovereignty and relevant place within the post-war world. The concept of *technopolitics* is particularly useful to shed light on how decisions over the reactor design were not merely engineering decisions. They were rather strategic practices through which technology was used to embody political goals such as national autonomy, military capability, industrial competitiveness and state-led modernisation. Following these reasons, the conflict between the CEA and EDF can be interpreted as a clash between two technopolitical regimes: a nationalist regime, centred on French technological autonomy and strategic power, and a nationalized regime, focused on electricity production, economic efficiency and the public-service mission of EDF. The strategic divergency culminated in the late-1960s "war of the

systems", which represented more than a mere technical dispute between gas-graphite and light-water reactors. It was a political and cultural turning point, because it counterposed different visions of France's technological future and reshaped the balance of power between CEA and EDF. The first design choice was undertaken by CEA that bet on gas-graphite reactors between mid 1940s and mid 1950s, when French nuclear program was under its control. Although government had not taken a favourable decision yet to produce the atomic bomb, CEA's reactors had already produced weapons-grade plutonium. A further reason to adopt graphite as moderator for power plants was the communist affiliation of many engineer who had worked on the experimental heavy water reactors, that represented another viable alternative. The result was the settlement of a five-year plan for 1952-1957 that included the production of two reactors, fuelled by natural uranium and moderated by graphite. The gas-graphite reactor design was politically powerful because of its ambiguity: it could be presented as a civilian technology for electricity generation and future reactor fuel, while also enabling the production of weapons-grade plutonium. Indeed, despite the declared goal was the employment of the reactors to produce electricity, the CEA's new Marcoule site in southern France demonstrated how technology could orient policymaking. Even before the French government openly committed to building an atomic bomb, the design of G2 and G3 made the production of weapons-grade plutonium technically feasible, further complicating an eventual political withdrawal. The Marcoule's G2 reactor design clearly reflected the priority given to plutonium production. As a matter of fact, the fuel-loading system was designed to remove irradiated fuel rapidly while the reactor was operating, a choice that made sense for producing weapons-grade plutonium but not for maximising electricity generation. Moreover, CEA wanted the reactors at maximum power all the time and this configuration could not be handled by an electrical network marked by variable energy demand. This constraint led EDF to add a *desuperheater* to the circuit to absorb the excess heat the network could not absorb. The rivalry between the CEA and EDF was therefore not merely an institutional dispute. It opposed two visions of nuclear France: one based on strategic autonomy, military power and national grandeur, and another based on public service, economic efficiency and the electrification of national modernity. Unlike CEA, EDF has been a bastion of the left throughout the years. Its nuclear power plant involvement began within the Marcoule reactors, through the addition of some small power generating units to the reactors. The gas-graphite configuration was suitable for the EDF ideological scheme of national design and production. EDF lacked the expertise, the financial resources and the time

to stand alone within the nuclear program and for this reason it started a cooperation with CEA to share technical and financial responsibilities. The joint effort of the two agencies resulted in the EDF1 project in which CEA was involved for the development of the nuclear parts of the reactor as the core and the fuel rods, while EDF was responsible for the design of the components for electricity generation. Undoubtedly, the clash between the two different regimes produced some tensions concerning the role of private industry within the project, together with reactor design choice. The CEA's political aims were not certainly hidden, as the agency wanted to extract plutonium for weapons development purposes. At the same time, EDF core objective was delivering a public service based on the *rentabilité* principle, which meant offer a national cheap and reliable electricity, while contributing to the broad social progress. Despite the conflict between the possible configurations, EDF1 reactor demonstrated to be a step ahead within the nationalised nuclear program, presenting common interest sharing. Among all, both EDF and CEA could benefit from the promotion of the nuclear program as a public service within the country, to pursue with their respective nuclear policies (Hecht, G., 2009). The early development of French nuclear power was not the result of a single decision, it was rather characterised by a sequence of technological, institutional and political turning points. After the creation of the CEA in 1945, the French programme entered an exploratory phase in which several reactor pathways were investigated in the name of national scientific ambition and energy independence. The initial choice of the UNGG reactor reflected the desire to develop a specifically French technology, while also maintaining links between civilian electricity production and strategic plutonium production. From the mid-1960s, however, the programme shifted from experimental phases to industrial planning, with economic criteria becoming increasingly important. This led to the "war of reactor systems", opposing the nationally developed graphite-gas pathway to the American light-water reactor technology, which appeared more mature and commercially competitive. The 1969 decision to abandon the graphite-gas option for industrial deployment and to adopt enriched-uranium light-water reactors marked a decisive turning point, making large-scale standardisation possible. At the same time, fast breeder reactors preserved the promise of a future autonomous nuclear pathway, later embodied by Rapsodie, Phénix and Superphénix. In this perspective, the 1974 Messmer Plan should not be seen as the sudden beginning of French nuclear power, but rather as a major acceleration of previous choices, pushed by the oil shock and supported by institutions,

expertise and industrial structures that had been gradually built since the post-war period (Le Renard, C., 2017).

French nuclear industry success story has its roots on some key success factors, of which the most important were the nuclear industry's military origin, the proximity among the main actors and the government and sometimes the direct state overlap. The impressive capacity to export its nuclear energy was developed during French nuclear golden age. After the Second World War, European countries tried to prevent the proliferation of atomic bomb in Europe with the creation of a treaty, designed under the European Defence Community Project. The community general aim was to protect Europe from nuclear threats during the Cold War and France was among the six member states signatory countries. However, in 1954 General De Gaulle announced the French production of atomic weapons, calling for national defence and rejecting the treaty previously signed by the country. Furthermore, when the general became president of the fifth Constitution in 1958, he had the complete control on nuclear weapons, as head of the French army. Public opinion struggled to easily accept the President personal control over this dangerous and powerful technology. Afterwards, De Gaulle power legitimisation resulted from an amendment to the presidential election procedure, which introduced the direct universal suffrage system. According to the Article 5 of the French Constitution the President is the guarantor of national independence. As military nuclear couldn't be alone the solution to ensure conformity with this legal statement, the shift towards civil nuclear power ensured the conformity with the French Constitution and increased public social acceptance. The desired independence from fossil fuels imports, especially from North American oil, boosted civil nuclear power development. In 1966, France left the North America Treaty Organisation (NATO) to strengthen its independence and reduce foreign interference. Even if electricity generation was fully covered, transports required oil and gasoline imports, downsizing the stated complete energy independence in the short-term.

EDF nuclear reactor projects started during the 1960s, along with a gradual electrification planning of the country to exploit nuclear electricity. The projects extension was supported through military fundings, indeed some civil nuclear investments came during the 1970s Arab-Israeli conflicts. Pierre Messmer, as Prime Minister at the time, announced an acceleration from the initial 8,000 MW planned installed power to 13,000 MW to be built between 1972 and 1977. The first oil crisis of 1973 tilted economies worldwide, giving civil power generation an important justification to grow and flourish, by offering an alternative to oil, too often affected

by geopolitical crises. It's important to highlight that the investment decisions and the subsequent nuclear plan revision were done before the outbreak of the crisis, demonstrating an independency route already started in the previous years. Certainly, the oil crisis influenced the 1974 Messmer plan *"Le tout nucleaire",* which planned the construction of 13 nuclear reactors, each one with 900 MW of capacity in the first two years. Only ten years later, 50 Westinghouse PWRs were under construction throughout France. The promise given to the citizenship was to pay back those huge investments by offering a cheap national electricity, free from foreign sources imports. (Stuart, C., 2017). The government considered nuclear energy as the best mean at its disposal to better control the growth of petrol imports that endangered energy and economic security of the country. The programme was perfectioned in accordance with the idea of increasing energy needs correlated with economic growth. In every case, France's industrial electricity demand was insufficient to meet the energy would be produced through atom. Consequentially, EDF attempted to stimulate domestic electricity demand, specifically with the implementation of a commercial policy aimed at the development of electric heating. The criticism and the doubts moved against the government led to the creation of a national expert commission on the use of heat in 1975, soon followed by a law adoption concerning heat use, complemented by the creation of a national heat agency. The expansion of nuclear power opened a debate over the possible uses of nuclear heat. The model that eventually prevailed was the fully electric nuclear regime, promoted by EDF and the French state: nuclear heat was converted into electricity, distributed through the national grid, and absorbed by the development of electric heating. According to the agency's idea, that type of electric heating represented a viable alternative in terms of yield in view of the other heating solutions, due to the minimal losses in the line and the possibility to rely even on distant power plants. However, this model was criticised for its low overall efficiency, since only around one third of the heat produced by reactors was converted into electricity, while the rest was released as waste heat. Alternative pathways were discussed, including nuclear cogeneration, which would have recovered both electricity and heat for district heating networks, and a mixed regime based on smaller reactors dedicated to urban heat production. The Bugey-Lyon studies and the CEA's Thermos project in Grenoble show that these alternatives were technically and politically considered. Nevertheless, they were gradually abandoned in the 1980s, as EDF's fully electric model became dominant. A further obstacle for the development of these prototypes was the President Mitterrand decision to renew the national support to the French coal industry. This

created a long-term path dependence, locking the French nuclear system into a centralised electricity-based regime and reducing the role of local or regional heat strategies. The fully electric nuclear regime caused irreversible changes to the overall French energy system through the rise of electric heating in urban centres. By way of illustration, in 1978 the new houses equipped with this technology exceeded 45%, while only eight years before struggled to reach 2%. The choice of this regime foreseen the exclusive electric recovery of heat generated by nuclear power plants. In this way, the extension of the national electric network guaranteed the absorption of electricity, justifying the prerequisites for an important nuclear program. The fully electric nuclear regime was closely connected to the principle of tariff equalisation and national energy solidarity. By converting nuclear heat exclusively into electricity and distributing it through the national grid, EDF and the French state physically separated the places of energy production from the places of consumption. This made it possible to apply a uniform electricity tariff across the country, regardless of consumers' distance from nuclear power plants. This model reinforced centralised governance, while framing nuclear electricity as a national public good, transforming the centralised nuclear system into an instrument of territorial solidarity (Fontaine, A., 2021). The idea of nuclear power as an energy imperative emerged while the oil shock was arising in the early 1970s. Therefore, the launch of the large nuclear programme in 1973-1974 marked the crystallisation of the French nuclear system. Its success was based on three main elements, such as the scale of the programme, the speed of construction and the systematic standardisation of reactors. EDF played a central role as architect-engineer, owner and operator, while the choice of PWR allowed French nuclear fleet to rely on an already tested and fine-tuned technology, lastly organising the expansion around the principle of industrial rationalisation. At the same time, the role of CEA evolved, indeed after losing the primacy over reactor construction to EDF, the organisation focused on research, nuclear materials and fuel cycle. The main reorganisation output was the creation of Cogema in 1976, which represented the general company of nuclear materials, responsible for uranium mining, enrichment, spent fuel reprocessing and waste management. The completion of the complete control of the entire nuclear fuel cycle was therefore another essential milestone achieved by French nuclear industry that further strengthened national strategic autonomy (Torres, F., 2018).

In the context of the two major oil shocks of 1973 and 1979, nuclear energy emerged as the strategic solution capable to ensure energy independence. The first European conference showed the optimism and the coordination of efforts of the European countries in the

development of long-term nuclear solutions. At that time, the potentialities of atom were considered pivotal to strengthen energy security and reducing geopolitical interdependences linked to fossil fuels price volatility. Nevertheless, Fast Breeder Reactors (FBR), nuclear waste management and fuel suitability still to be implemented in the period of the first conference. In 1976, while the world was struggling with the aftermath of the first oil shock, the CEA General Administrator Giraud underlined the unstoppable growing of energy demand at global scale and the consequential improvement of human life conditions. In his view, this pathway could be performed with the gradual phase-out of oil and coal with and unavoidable adoption of nuclear energy, by foreseeing a continuous development of PWRs. Despite these promising beliefs, at the end of the 1970s coal price remained more competitive compared to nuclear heating applications, demonstrating an unadapt solution, considering the size of French heating system of the time and therefore the reduction of possible application of atom other than electricity production. At the end of this decade, in a general nuclear energy growth context, Eurodif was launched by a consortium of four countries to establish an autonomous supply of enriched uranium through gaseous diffusion technology, while U.S. almost ruled the enrichment market. This installation proved the implementation of a European coordinated effort and it contributed to the fuel cycle efficiency, by giving more autonomy to the French nuclear fleet. Even so, French nuclear electricity faced a steep increment in kWh cost during the 1970s because of the capital-intensive structure of the projects and the too optimistic early projections. Straightforwardly, safety measures and materials compliance necessitate longer building times which delayed revenues and extended the payback period of nuclear power plants projects compared to the traditional oil and gas generations (SFEN, 2025).

In the 1980s France became leading power for production of electricity from nuclear power, despite during the previous decade the country had to deal with the stronger anti-nuclear energy movement in Western Europe. The international oil crisis gave the opportunity to nuclear opponents to emphasize the issues arising from the clubbish decision-making promoted by French nuclear industry. Despite this lack of citizenship involvement, nuclear energy popularity gained popularity and consensus. Indeed, through the energy produced from this source, France could accelerate its energy independence process avoiding the appeal to foreign energy sources. The dissent against nuclear weapons proliferation within France had its beginning in 1959 with the foundation of an organization opposing to military applications of this technology. Although the strong commitment of this first organization, atomic bomb was introduced as a new item in

the military arsenal of the country in 1960 and this was followed by President De Gaulle announcement of nuclear testing in Sahara. The anti-nuclear movement was established in 1962 and reached its popularity peak in 1977 when 60,000 demonstrators marched against Creys-Malville nuclear power plant. The demonstration ended up into a violent confrontation with the police, in which one demonstrator died, and several were injured. The anti-nuclear movement have revealed the political and social tensions generated by the rapid expansion of nuclear power during those years. Despite the relevancy of the event, French government didn't decrease its pace and continued the expansion of the nuclear energy program, encountering weak and insignificant resistance from the anti-nuclear energy movement. The protest in France didn't have a great success because they had to face the strong executive power and at the same time a weak legislature that allowed streamlined procedures in favour of nuclear development. Furthermore, civil society was not so developed as well as the voluntary association system. The absence of a well-established civil opposition field jeopardized these mass mobilization attempts, compromising the admission to political decision-making. The situation worsened in 1972 when socialist and communist agreed on a common policy over nuclear weapons and with the decisive turn of 1977 when both left-wing parties jointly confirmed their support to French nuclear weapons. During the 1980s, France maintained a distinctive position within the Western security system. Although it remained politically aligned with the West, its nuclear doctrine was based on national autonomy rather than full integration into NATO's nuclear strategy. As a result, the new pan-European anti-nuclear movements had limited influence in France: the country did not host NATO cruise missiles, and its nuclear deterrent was framed as an independent instrument of national sovereignty. (Litmanen, T., 1998).

The 1980 French government energy policy for the next ten decade represented a clear attempt to shift towards national energy independence. This strategic move had the aim to impact France economy but even ensure national security through the increase of nuclear and its military synergies within the country's energy mix. In spring of 1980, the French energy policy foreseen the passage of nuclear share as energy source from 4.5% to 30% by 1990. The reasons behind that strategy were the historical scarce presence of fossil fuels in the national territory, along with a hydro-electric sector almost fully exploited. Within this framework, nuclear role could avoid energy shortages and reduce the excessive dependence on foreign oil that accounted for the 45% of energy supply at the time. Moreover, atom energy could help to better deal with Middle East oil supply vulnerabilities, consequentially to the oil price steep rise. The

successes obtained during these first programme's phases is largely due to institutional and political factors. Nuclear industry represented an evident monopoly structure involving CEA for research and fuel cycle control, EDF for property and management of electricity infrastructures and Framatome as the builder. This high concentrated power allowed the system to ensure competitiveness, experience and security, while endangering public dissent. Additionally, opposition had less opportunities because it was use weak, fragmented and poorly financed compared with other countries. Even the support of socialist and communists played an important role as they traditionally largely dominated the CEA. Hitherto, French nuclear development had faced hindrances both at technical and economic level, but even social, moral and environmental concerns. The costs to bear to fund the subsequent programme phases were difficult to sustain during a period of recession. Despite the disorganized public opposition, the growing concern regarding waste disposal, environmental hazards and risk of accidents put pressure on the industry which dealt with continuous technical delays to comply with stringent safety controls. Although, the programme promised international energy independence, the program generated also dissatisfaction amongst many of the French people who feared the strengthening of the technocratic control could lead to the so-called *électro-fascisme* (Boyle, M., Robinson, E., 1981). After the completion of the 1980s construction programme, the French nuclear system entered a more mature period which marked the beginning of a new phase. The issue was no longer the rapid expansion of capacity, instead the management of an already installed reactor fleet, the search for export markets, the treatment of spent fuel and radioactive waste and the gradual strengthening of nuclear safety governance. The French nuclear trajectory was modified less by a linear technological evolution than by successive institutional and industrial game-changing events. In this sense, the 1980s and the 1990s characterized the transition from nuclear construction phase to the nuclear energy management one (Torres, F., 2018).

In the decade 1985-1994, the main destabilizing event was the 1986 Chernobyl accident. Despite several European countries scaled down the range or withdraw themselves from the nuclear journey, France chose to keep its nuclear commitment without changing the production targets set before the disaster. This unchanged engagement had greater value, given the decline of nuclear projects worldwide and the not so linear support of President Mitterrand during his two legislations (1981-1995). The start-up of Superphénix clearly demonstrated the extent of French nuclear ambition, even shortly after the most sever nuclear accident never happened

before. Conceived as an industrial-scale fast breeder reactor, it embodied France's ambition to move beyond the conventional pressurized water reactors and to develop an advanced nuclear system based on a better management of uranium resources and the plutonium recycling. The endeavour had a strong European dimension, since it included the cooperation between EDF, ENEL and RWE, the respective French, Italian and German energy companies. The owning and management of the power plant was under the control of NERSA, the European consortium created for Superphénix project handling. The society was created in 1974 with the following ownership structure: EDF owned 51%, ENEL owned 33% and RWE owned 16% of the company. However, its location at Creys-Malville, close to both the Italian and the Swiss borders, transformed it from a symbol of European technological cooperation into a challenging transboundary controversy. The project was authorized in 1977, during the peak of French nuclear expansion, despite receiving great opposition since the initial phases. From the late 1970s onwards, Superphénix became the target of anti-nuclear protests, scientific counter-expertise opposition and legal challenges, especially due to possible safety and plutonium related risks underlined by the French and Swiss actors involved. Superphénix history was marked by technical difficulties, repeated stoppages and growing political opposition. In the subsequent years, in several countries academics tried to influence the course of FBR projects highlighting the economic inefficiency of this type of reactor. In addition, the lack of standardisation across countries further complicated the realisation of the advanced design and the engineering modelling. Applying these reasonings to the specificities of Superphénix we should also consider the presence of coordination costs necessary to deal with the transnational scope of the project. In this sense, its early closure represents a key turning point because it revealed the limits of France's fast breeder strategy and marked the transition from the expansionist optimism of the 1970s to a more contested phase of French nuclear policy, centred on safety transparency and public acceptance. On the contrary, the standardisation effort succeeded for LWR, redirecting French nuclear programme, as demonstrated by the massive orders to the national industry for this competing type of reactor. Superphénix entered operation in early 1986, only a few months before the Chernobyl accident, however even before the legal decree for its authorisation EDF judged the design too expensive for a future marketable FBR. This is significant because its start-up took place just as the international nuclear context was about to change radically: after Chernobyl, safety, transboundary risks and the social legitimacy of nuclear power became much more central issues. In 1989, through a new authorising creation

decree was granted a provisory restart of the power plant. However, there was the possibility to infringe Article 34 of the Euratom Treaty, because of the risk of affecting neighbouring countries through "particularly dangerous experiments". In the 1990s, following technical problems and legal controversies, the reactor was requalified as a research facility: electricity generation became secondary to research, particularly on plutonium and the future of fast breeder reactors. Moreover, FBRs were largely considered too expensive and not so useful as the concerns about fuel scarcity were ended as well as the nuclear global development scenario was drastically changed from the expectations drawn in the early 1970s. In 1997, the Prime Minister Lionel Jospin announced its closure, which was formalised in February 1998 with a decree that ordered the beginning of the decommissioning phase, by ending the plant operating time while starting the deconstruction period (Le Renard, C., 2018). In 1996 French Court of Auditors estimated 0.760 billion € for Superphénix decommissioning, a figure further increased until over 2 billion € by 2003. Considering the entire lifetime power generation of about 8.3 TWh, this power plant produced electricity at 1.35 €/kWh compared with the French feed-in tariff of 0.55 €/kWh in 2010 for renewable energy technology integration. From the financial dimension these figures highlight the economic irrationality to carry out this type of project within EDF political framework and respect of *rentabilité* principle (Schneider, M., 2010).

The strong will of becoming one of the most relevant nuclear actors worldwide resulted in the European Pressurized Reactor (EPR) project of 1994. Innovation and technological export were at the center of the coordinated German-French commitment during the project steps. At the beginning of 1990s, the growing energy needs boosted the development and the conception of the EPR, which represented an upgrading of PWR reactors and the experimental phase of the third-generation reactors. The objective of the two conceiving countries, France and Germany, was the planning of a standardised product suitable to several potential sites, considering the remaining limited availability of exploitable locations in both nations. Since the first steps, the project development was characterized by a common effort of the safety authorities and the main nuclear actors of the two countries. The planned key features of this generation of reactors were the augmented power up to 1500 MW, an extended life cycle (60 years), an optimised fuel cycle, with the general aim to increase the number of operating hours per year. All these factors were supposed to prevent and reduce major accidents like core fusion. The upgrading of protection system against internal failure or external attacks had greater relevance, given the short time distance from Chernobyl accident. Particularly, the provision to build an aircraft

shield to prevent terroristic attacks, while the Cold War was already terminated, assumes a major resonance considering the September 11 attacks happened some years later.

Together with the efficient management of civilian and military nuclear production activities, nuclear French industry directed some financial resources to the launch of initiatives and programmes facing the development of decisional supporting systems (*Système experte*) and the inclusion of women into the public opinion debate on nuclear energy to better reach and communicate with them. The first primordial example of AI (Artificial Intelligence) within French nuclear occurred in 1987 with an expert system aimed at formation and support of operators in the accidents transitory phases. The system was called *SEPIA,* it was realised by Framentec, a start-up of Framatome focused on AI system development. The program utilised the real-time reactions of operators and other data coming from the simulator to build a dashboard machine-man. This pioneering system allowed an augmentation of work sessions delivering advice and explanations based on human expertise. Concerning the problem of distrust or lack of interest of female gender about civilian nuclear energy, in 1993 the foundation of Women in Nuclear (WiN) was an example of nudging towards nuclear support. The real issue was indeed the low participation in nuclear debate, rather than the workplaces occupied by female employees who covered around the 24% of the entire nuclear supply chain, even if they were underrepresented within research and technician roles.

Between 1995 and 2004, the global nuclear landscape approached both a stagnation in some countries and in other like France the pursuing of cutting-edge technology development within nuclear industry. Specifically, the recycling and waste management was strengthened by the evolution of MOX (mixed oxide of plutonium and uranium) fuel that represented an alternative to enriched uranium coming from plutonium and other decommissioned nuclear weapon waste. Despite the pivotal independency push that this type of fuel could give to the nuclear industry, resulting in a lower reliance on enriched uranium, MOX is more radioactive, radiotoxic and thermally unstable compared to the former fuel. Nevertheless, it enables the valorisation of fissile materials waste and the recovery of elements with high energy value. In 1985, the EDF reactors were turned to the use of MOX and this orientation explains the later opening of Melox, a facility that manufactures fuel from plutonium recovered through spent fuel reprocessing and depleted uranium. Still nowadays, the valorisation of plutonium has gained importance after the current fleet renewal decision. Since the opening in 1995, Melox factory has produced more than 3100 tonnes of MOX fuel, providing it to more than 40 reactors located in France and

abroad. Today, this facility is the only one worldwide able to serve Light Water Reactors (LWR) that functions with the mixed fuel configuration (SFEN, 2025).

In 1995 France conducted an underground nuclear test in Polynesia, to complete a test plan series before the signing of a comprehensive test ban treaty (CTBT) one year later. President Chirac remained determined to complete the test series in order to avoid further future tests and the public opinion emphasis about the theme overshadowed broader long-term nuclear dilemmas that interested the country. French government claimed that their nuclear testing wouldn't cause any impact on the aspirational nuclear countries' choices and disclosed them in a transparent way. At that time, a no test-regime could impact on safety and reliability of France's nuclear stocks and lead to potential dependencies on U.S. Some French strategic analysts highlighted the limitations of CTBT, pointing out the risk of untrue low-yield tests declared, the expansion of uncontrolled nuclear proliferation without a testing framework. In a certain way, tests allow a better control of the technology use. Nonetheless, French officials supported the treaty believing in its proliferation stopping potentialities and to comply with the more stringent international context requirements. In 1996 there was the first opening to a possible extension of deterrence in function of EU defense, a sort of so-called deterrence "Europeanization". This triggered some doubts concerning the credibility of this action, as the Cold War was already ended and France had just resumed its testing effort in the Pacific through a unilateral decision breaching multi-consultation obligation. Nuclear bomb use was admitted under specific circumstances, for instance against an adversary intentioned to use weapons of mass destruction. France's policymakers and analysts identified two traditional approaches to deal with deterrence theme: the more operational approach and the less operational approach. The first one supported deterrence as a possible mean to use through control and discrimination of flexible military capabilities, while the latter remained anchored to the traditional French deterrence policies, envisaging massive strikes and opposing to limited nuclear options at disposal of the government. The French doctrine according to Chirac was the privileging deterrence actions rather than the use as combat arms. France's president shed light on the problem of low-yield weapons that resulted more dangerous due to the ease of their production and their undiscriminating potential use. However, the commitment in nuclear proliferation avoidance could harm national defense interest under CTBT conditions as France couldn't directly threaten nuclear attack. Criticism arose from both EU and U.S. defense analysts regarding opportunity costs of maintaining nuclear deterrent in place of conventional military

technologies. Furthermore, cutting financial resources dedicated at military nuclear budget was a possible solution to reduce French deficit. Despite the economic rationale of these proposals, even the socialist part of the government never argued France independency on the matter and justified testing activities. The advisors of nuclear weapons have always pointed the association between the deterrence and the national independence status, together with the security offered against another world war. Since the late 1950s with the experimental phases of nuclear weapons, they have guaranteed political and strategic autonomy, while facing a hostile and unstable world (Yost, D., 1996).

The early closure of Superphénix in 1998 had his root in the intense political and societal pressures received since the start of the project and it represented a clear turning point in the breaking of decision-making hegemony. The stop of the nuclear power plant came with a political agreement, despite when it came to life it represented the answer to oil shock of 1973 and a driver of energy independence against geopolitical instability. Among the several factors responsible of the premature closing, it's important to mention the delays and periodical turning off due to recurring technical failures and administrative procedures. Together with the technological complexity challenges faced during the Superphénix life, one could question if this even could be also considered as the greatest ideological failure of nuclear top-down solutions. However, in the subsequent years, nuclear energy held its place of fundamental energy pillar of the country. With the beginning of the new millennium, nuclear started to reposition itself as a low-carbon alternative within a framework of growing climate change concerns and was brought as a central theme in the energy national discussions. The challenges and pressures of the new centuries didn't obstacle the pathway undergone by the French atom. France wanted to confirm its knowledge expertise without complaining about its model, while carrying on its research on long-lived radioactive waste and renewing its enriching plant George Besse II. In these years, there was the first debate concerning energy in France, strongly encouraged by the President Chirac. The importance of the current and future energy policies discussions resulted in the 2005 "*Loi Pope*", that ruled the planning of French energy strategies. On the background, the climate change challenge and the enumeration of all the possible low-carbon solutions, of which hydrogen and nuclear, represented the core of the debate. Furthermore, it was underlined that to shrink energy consumption was necessary to increase electricity consumption by fostering the low-emitting resources available.

The emergence of adoption of renewable energy sources solutions characterized also the years 2005-2014 due to the growing energy needs of the country and the threat of climate change. In France, the end of the contractual phases of the first EPR located in Flamanville in 2005 emerged as the general will to modernise the entire industry, even if the reactor has been connected to the grid only two years ago. This modernizing push was confirmed by the President Chirac's announcement about the political support to the realisation of 4th generation reactors. Prompting the effort towards this direction, the president assigned to CEA the conception and construction of the new reactor generations within the 2040-time horizon confirming his will to maintain French domain on atom. CEA emphasized the challenges regarding safety measures and economic competitiveness of such new technology, underlining the idea of utilising the new reactor for hydrogen production. Moreover, the industry actors sustained the expected complementarity between the fourth-generation projections with the ones of the EPR. Noteworthy, mentioning how the growing restlessness arising from energy independence and security, the steep rise in fossil fuels prices and the carbon dioxide emissions boosted the appeal to atom energy in a certain number of countries. In 2006, President Jacques Chirac announced the creation of an independent nuclear safety authority in order to strengthen public confidence, transparency and state control over nuclear activities. The Law on Transparency and Nuclear Safety (2006) established the *Autorité de sûreté nucléaire (ASN),* an independent administrative authority responsible for supervising nuclear safety and radiation protection in France. This law constituted the long-awaited framework law for the nuclear sector: its objective was indeed to better regulate the creation, exploitation and phasing-out of nuclear installation. Along with the creation of ASN that was an organisation independent from the government, this law unbundled the nuclear activities, establishing which were the civilian nuclear activities and installations, aimed at a further improvement of efficiency. ASN also contributed to the elaboration of the PNGMRD, a national plan for the radioactive material and waste management. The elaboration of this plan foresees the active engagement of citizenship through the communication and dissemination of the implications of these radioactive residuals and the research conducted. The plan's transparency resulted in the presentation and explanation of the different storage and disposal applicable for the waste and materials, as the industry didn't own a permanent solution yet. Despite, the declaration of potential threats coming from disposal process, this primordial plan aimed at preventing the detriment for future generations, caused by the utilisation of resources for current generation, highlighting this

intertemporal and intergenerational constraint. It must be acknowledged how relevant could be this untouched commitment within a global economic crisis framework where new projects faced challenges in funding raising. In just a few years, the sovereign debt crises (2010) and the Fukushima accident (2011), turned this optimism towards a political scepticism. Indeed, the declared reduction of nuclear energy within the French energy mix and the possibility to shut down the reactors under the François Hollande presidential term, presented a serious threat to the whole nuclear supply chain. On March 2011, the Fukushima power plant accident was the consequence of a powerful earthquake and a tsunami, that passed the barrier, destroying diesel generators and causing overheating and the consequent hydrogen explosions and core fusion of the three reactors and eventually the release of toxic substances in the air and the water in the surroundings. As a result of the disaster, several countries, like Germany and Switzerland decided to progressively reduce their stake of nuclear within the energy mix, while in France EDF aftermath was the launching of a vast renewing of safety measures through the so called "Grand Carénage" program. This was the first major disastrous event after 25 years, classified at the maximum level of the International Nuclear and Radiological Event Scale (INES), as well as the Chernobyl one. Although the new safety measures upgrading program, within French nuclear industry there was the lack of qualified personnel of intervention in case of emergency. Then, EDF put in place FARN (Force d'action rapide nucléaire), a special unit able to intervene for events of this scale.

In 2015, given the threat of climate change to deal with, during COP21 nuclear was repositioned as an important low-carbon energy asset. There was stressed the potential complementarity between atomic energy with renewable energy sources (RES). The COP21 should be considered as an updating of the Kyoto protocol, with the important difference of the inclusion of nuclear among the energy source solutions. As the result of the final agreement, 195 nations set the objective of limiting global warming with a bearable increase between 1.5° C and 2° C, compared to the preindustrial levels, by 2100. The nuclear community through the initiative Nuclear4Climate, carried out with the collaboration of the European Nuclear Society (ESN) and the American Nuclear Society, raised its voice to be considered among the panel of possible solution. Atom further expansion was still limited and not yet conceived as a strategic low-carbon solution. Within the framework of amplification of pressure on the environment and the growing concerning about climate change consequences, many developed economies choose to set their own CO_2 reduction objectives, through for instance sectors' electrification and coal

decommissioning. Climate change can lead physical risk, involving and impacting all the nuclear installations increasing the probability to suffer damages or asset losses due to extreme events like floods, droughts, heat waves and even hurricanes. All these occurrences are heavily influenced by the steep rise in Greenhouse Gas Emissions (GHG), that drive global warming side effects. Despite, the demonstrated low-carbon impact of nuclear activities, at COP24 (2018) was still visible a strong resistance against nuclear adoption and expansion as a possible strategy towards net-zero objectives. Among all, the principal opponents were the environmental Non-Profit Organization (NGO) that underlined solely the threats deriving from nuclear hazards and accidents and the potential damages to the environment, without considering the opportunity given by nuclear in this transitory phase to help phasing-out fossil fuels. In 2023, COP28 became an important platform for the repositioning of nuclear energy, as more than twenty countries endorsed a declaration supporting the tripling of global nuclear capacity by 2050. Furthermore, it was the first time nuclear was mentioned in the final agreement. In the meantime, France still went on with its diversification effort, for instance through Areva Med it's been discovered the use of Pb-212 against cancer and still with the proliferation of new nuclear actors complementary to the incumbents. Despite the later outbreak of Covid-19 in 2020 shocked the maintenance program of nuclear fleet, it demonstrated at the same time how nuclear is a sovereign strength against unexpected and disrupting global crisis. Again, even if is arguable if nuclear energy should be considered at the same level of a green technology, it's not questionable the supply of resilient and controllable electricity coming from this energy source (SFEN, 2025).

3.2 The role of nuclear within the French energy mix

Summarizing, French nuclear electricity generation followed a long-term expansionary pathway from the start of the 1970s onwards, instead of reacting immediately to single historical shocks. Although the trajectory to follow was already set before the 1973 oil shock, in every case the effects of nuclear in the country's energy mix became visible only gradually considering the long building and commissioning timeframes required by nuclear reactors to be operating. By contrast, the Chernobyl accident in 1986 did not produce any downfall in French nuclear generation, indicating that France maintained its yet determined nuclear journey, while strengthening the regulatory and safety dimensions of the sector. In a similar way, Fukushima in 2011 had an important political and regulatory impact than an immediate production decline

effect. The most visible disruptions appear in the recent period, with Covid-19 crisis and the 2022 availability crisis, when maintenance constraints and technical failures reduced nuclear output. In general terms, French nuclear sector has been shaped less by near-ter geopolitical disrupting events or accident-related shocks than by long-term industrial commitment, national energy policies, fleet availability and regulatory adaptation. Overall, the French case shows an impressive continuity in nuclear electricity production, covering the 44% of total energy supply and the 76% of total domestic energy production (IEA, 2024).

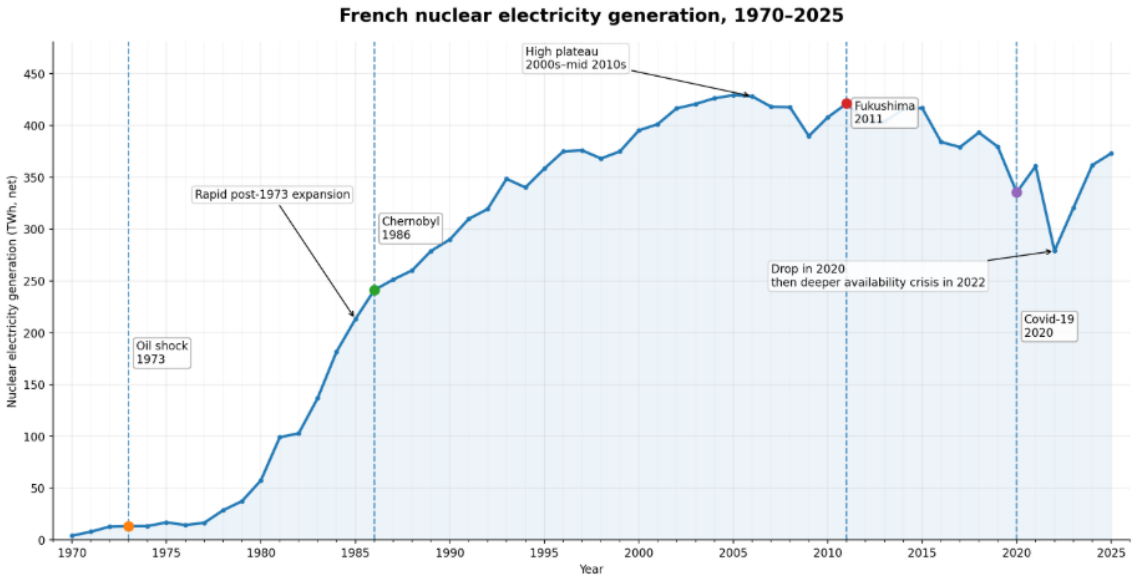


Figure 3.1: French nuclear electricity generation with major historical events (Source: EDF SA historical production dataset, values converted from GWh to TWh)

The role of nuclear energy within France's electricity mix is considerable and it has a key role in reducing GHG emissions and achieve climate neutrality through its low-carbon and affordable providing of electricity that ensures country's energy independence. In France, nuclear power has traditionally provided baseload electricity, ensuring a stable and continuous supply for the national grid. However, because nuclear represents such a large share of the French electricity mix, reactors also need to operate flexibly by adjusting their output to demand variations. This load-following capability makes the French nuclear fleet more adaptable than a purely baseload system and strengthens its role in electricity security and low-carbon system stability. If we consider the short time horizon, nuclear energy constitutes the pillar of French electricity supply, besides contributing to ancillary services and system stability through inertia

and frequency control. Despite the decarbonisation and net-zero requirement to the electricity sector by 2050, in most scenario nuclear energy will continue to play a pivotal role. However, every time a policymaker plans the possible future contribution of the current nuclear fleet, them should consider the average age of the reactors. A prevention action to deal with aging concerning long-term operations has been the so-called *Grand carénage* program for the refurbishment of nuclear reactor components, preparing them to last beyond 40 years. French law does not establish a maximum lifetime for a nuclear power plant, although every ten years a safety review must be conducted, generating safety improvements and recommendations. According to the estimates of EDF, the estimation of cost to perform the program accounts for EUR 49.4 billion, considering the 2014-2025 period alone. Considering a ten-years as well as a twenty-years scenario, nuclear should offer a cost-effective and low-carbon electricity bearing the cost of around USD 30/MWh. The French nuclear industry is vertically integrated in all segments of the fuel cycle. The sector is organised around a strongly state-centred structure, indeed French government plays a strategic role as shareholder, policymaker and guarantor of energy security. EDF occupies the central position as owner and operator of the nuclear fleet, being responsible for plant operation, maintenance, engineering and decommissioning. Framatome, controlled by EDF, provides the industrial and technological expertise required for reactor components, fuel assemblies and nuclear services. Orano is responsible for key stages of the nuclear fuel cycle, including uranium mining and conversion, as well as enrichment and reprocessing, while the CEA remains the main public research and innovation body within the nuclear field. Waste management is entrusted to ANDRA, the national agency responsible for long-term radioactive waste solutions. Finally, nuclear safety and radiation protection are supervised by the independent ASNR, created in 2025 through the merger of ASN and IRSN. Overall, this structure shows that the French nuclear model is not simply an electricity-production system, but an integrated national industrial and regulatory framework covering the whole nuclear chain, from research and fuel supply to reactor operation, safety control and waste management (IEA, 2021).

Reactor type/series	N°of reactors	Unit capacity	Commissioning period	Approximate age in 2026
PWR – 900 MW series	32	Around 900 MWe	1978-1988	Around 38-48 years
PWR – 1300 MW series	20	Around 1300 MWe	1985-1994	Around 32-41 years
PWR- N4 series	4	Around 1,450-1,500 MWe	2000-2002	Around 24-26 years
EPR – Flamanville 3	1	Around 1,600-1,650 MWe	Grid connection in 2024; ramp-up in 2025-2026	Around 1-2 years

Table 3.1: Overview of the current French nuclear fleet main features (Source: EDF-URD, 2024)

In 2024, French primary energy production reached 1,564 TWh, increasing by almost 10% compared with 2023 and returning to its pre-crisis level. This rebound was mainly driven by nuclear energy, which accounted for 74% of domestic primary energy production, corresponding to around 1,153 TWh. The recovery was linked to the improved availability of the reactor fleet, including the restart of several units and the shortening of outages related to the stress corrosion phenomenon identified at the end of 2021. Nuclear power also remained the largest component of French primary energy consumption, representing about 41.3% of the primary energy mix in 2024, ahead of oil, natural gas and coal. This confirms that nuclear energy is not only central to electricity generation, but also to the broader structure of French energy supply. In the same year, net electricity generation reached 548 TWh, with nuclear generation increasing by 13% to 362 TWh. Together with strong hydropower production, this recovery reduced the need for thermal power plants, whose output fell by 24% to 37 TWh. In this sense, nuclear availability directly affects the carbon intensity and security of the French electricity system: when the nuclear fleet performs well, France can limit fossil-fired backup generation and strengthen its position as a net electricity exporter. Nuclear power also plays a major role in France’s energy independence. The French energy independence rate reached 60.7% in 2024, its highest historical level. The long-term increase of this indicator is closely linked to the implementation of the nuclear programme in the 1980s, while its temporary decline in 2022 reflected the reduced availability of the reactor fleet. The subsequent recovery confirms that nuclear power remains a central component of French energy sovereignty, even

though its contribution depends strongly on reactor availability and long-term maintenance performance (Service des données et études statistiques, 2025).

In 2025, French nuclear production has been 373 TWh, with a 3% increase compared to the 2024 levels. This figure shows the restabilizing process to a level close to the one before the stress corrosion cracking crisis of 2021-2022. Specifically, during this timeframe 65% of the fleet has been stopped due to extraordinary maintenance, affecting even the planned ordinary one. The Covid-19 aftermaths didn't certainly help to deal with the unavailability of the power plants and for the first time since 1980, France has returned to be a net energy importer. The heavy reliance on nuclear for electricity production within the country could be problematic during technical emergency like the one just illustrated. This situation has endangered the France's energy security, while revealing the systemic importance of nuclear availability in the country. The sharp decline in nuclear output was partly offset by higher gas-fired generation and increased electricity imports, while coal remained marginal. As a result, the crisis moderately increased power-sector emissions, showing that reduced nuclear availability can temporarily weaken the low-carbon performance of the French electricity mix. The nuclear fleet availability rate was 74% in 2025, re-establishing and overcoming the values of the year prior to the crisis (e.g. 71.6% in 2019). Diving deeper with the monthly availability rate we can notice higher rates in January and February when the greater energy demand is a challenge for energy security. In order to guarantee and maximise the winter availability, the interventions are scheduled during spring and fall seasons to avoid further pressure in the crucial months. The French nuclear fleet was designed since the beginning in a load following mode, based on weekly and even daily energy demand variability. Furthermore, the adaptation to heating system electrification has led to a lower nuclear energy consumption during nights and weekends. Yearly, some energy is not produced because of planned maintenance and modulation, that refers to the ability of nuclear power plants to adjust their electrical output according to the needs of the power system. If all reactors operated permanently at full power, the system would face difficulties during periods of low demand. Therefore, part of the French nuclear fleet is operated flexibly, allowing output to be adjusted to demand variations. Although flexible operation increases the adaptability of the French fleet, nuclear reactors remain capital-intensive assets that are economically most efficient when operated at high load factors. Nuclear modulation is operated in form of shutdowns or through the lowering of reactors power, while maintaining them under operations. Often, these planned stops follow the refuelling schedule

that must be done between 12 and 18 months, with modulation applied to get to the next recharging smoothly. In 2025, the total non-produced energy accounted for 80 TWh, of which recharging operation as the main driver and with around 30 TWh due to modulation actions (RTE, 2026).

3.3 Recent developments in the French energy sector

In the most recent years, France is lagging with the implementation of energy transition, though has updated a clearer measures' framework. The 2020 energy efficiency and renewable energy sources integration targets have not been reached. The threshold of 130 million tonnes of oil equivalent (Mtoe) within energy efficiency area has not been fulfilled, as the final energy consumption was 145.5 Mtoe in 2019. Despite, RES generation has increased until 23.4% in 2020, starting from 14% in 2010, additional PV and wind capacity is necessary to remain aligned with emissions targets. In 2019, the country has satisfied half of its total energy supply (TES) with its domestic energy sources. France's domestic production included nuclear energy (79%), bioenergy (13%) and even other renewables, such as hydro (3.7%). Furthermore, nuclear energy accounted for 43% of TES in that year, followed by imported oil, natural gas and bioenergy. In the period 2010-2019, nuclear energy share within national electricity mix has been quite stable, while coal supply decreased by 55% and natural gas suffered an 18% reduction. Moreover, coal supply shrinking brought down the share of electricity produced through this energy source. France records the lowest fossil-fuel share among G20 countries, largely because of its strong reliance on nuclear power generation (IEA, 2021). The problem of assessing uniquely the share of nuclear in the French electricity mix is because that level does not represent the country's total energy consumption. Although it accounts for 70% of electricity production, it corresponds only to less than 20% of final energy used in France.

The year 2022 has been marked by the most serious energy crisis since 1970s oil shocks. Russia's invasion of Ukraine argued European security of supply, excessively based on foreign gas imports, that was already under stress due to Covid-19 aftermath. Furthermore, a crisis of French nuclear power generation worsened the already compromised situation. The nuclear fleet was affected by a stress corrosion phenomenon which forced several shutdowns for testing and repair activities. Therefore, nuclear power output yearly average recorded its lowest level since 1988, 30% below the past 20 years figures. Additionally, hydropower output declined to

its lowest level since 1976 due to a prolonged drought experienced throughout Europe. Despite this challenging backdrop, French power system proved its resilience, avoiding supply chain disruptions. The reasons behind this outcome are the reduced power demand in France and the economic effects generated by the crisis. Indeed, France experienced sharp prices increase, as hydropower and nuclear outputs significantly dropped. Once many nuclear reactors have been put back into operations, uncertainty on prices gradually disappeared. The energy crisis even generated a contained environmental cost via direct emissions from electricity production: 25 MtCO2eq against 21.5 MtCO2eq in 2021. As coal-fired generation is almost phased out within French power mix (around 0.6%), gas-fired were largely dispatched, answering to legacy sources unavailability. However, country's emissions level was far below those of comparable countries like Germany. Even including imports from neighbouring countries, carbon footprint generated by power consumption was not significantly deteriorated. In 2022, energy transition did not experience slowdowns, and this is demonstrated by the 5 GW of renewable capacity added. The same year, total electricity consumption decreased by 1.7% from 2021, reaching 459.3 TWh, a drop similar to the one happened after 2009's financial crisis. On demand-side, exposure to energy prices volatility and absence of clear countermeasures led to an industrial sector demand reduction, confirming the European trend. Household consumers put in place energy savings behaviours to deal with price hikes and economic constraints. Even French government was engaged in the implementation of energy sobriety measures to support the downward trend in consumption. The unseasonably warm temperatures of that year led to a huge reduction in power demand, underlining the temperature-sensitivity of French energy demand. Total electricity generation recorded the lowest output since 1992, considering a nuclear fleet under construction yet at that time. Nuclear energy produced 82 TWh less than in 2021, while hydropower generation experienced a 12 TWh reduction. These declining outputs have been partially replaced by an 11 TWh gas-fired generation, complemented by a 4 TWh solar increase. French nuclear availability rate has recorded is all time low in August 2022, recording 21.7 GW. Around 65% of nuclear power plants were offline, due to stress corrosion that further provoked unscheduled outages and extraordinary maintenance. Consequently, annual nuclear output felt to 279 TWh, compared to 379.5 TWh provided in 2019, corresponding to a level 30% below the prior 20 years average. This nuclear availability downsizing has been even complicated by yearly rainfall deficit which impacted power plants water cooling systems. Furthermore, yearly rainfall shrinking impacted the availability of

hydropower capacity, with water reserves dropped to low-bounds historical levels. Security of water supply has been guaranteed by hydropower efficient management and supported by fall months favourable weather. Reduced capacity and lower demand enabled the restoration of normal conditions in winter months. Nonetheless, hydropower generation decreased by 20% compared with 2014-2019 average levels. Yearly final output was only 49.6 TWh, instead of 67.7 TWh recorded in 2018. Moving to renewable energy integration, the commissioning of the first offshore wind farm, with 480 MW of capacity, represented a main event for French renewable capacity evolution. At the same time, onshore wind scored the lowest capacity factor in ten years (21.6%). Solar output increased by 31% from one year to another, producing n output equivalent to three nuclear reactors in volume (18.6 TWh). In 2022, gas was the third largest electricity source, behind nuclear and hydropower. Even if the worse scenario consumption projections did not turn out, gas-fired plants reached a yearly output of 44.1 TWh (+11.2 TWh from 2021). This important dispatchment was necessary to cover hydropower and nuclear shortages. Before 2022, France had not been a net importer of electricity since 1980. Indeed, the net import balance was 16.5 TWh, though representing only 4% of total domestic consumption. Although French energy exports are maximised especially during summer months, nuclear and hydro supply substantial unavailability led to 10 TWh of imports in that season. However, France exploited relatively cheap and abundant generation from neighbouring countries, that benefitted from favourable weather conditions, having at their disposal renewable energy sources in excess. Anyway, the country was a net importer almost 70% of the time in 2022, depending on energy imports to ensure national security of supply.

The unprecedent increase in gas prices and the growing security of supply concerns resulted in an electricity price surge of both spot and forward prices over short and long terms. During August 2022 last week, spot prices set an average price of 612 €/MWh due to nuclear and hydropower limited outputs. Moreover, forward markets highlighted the existence of a specific risk premium for France. This was the result of excessive hedging actions planned to prevent supply-related risks. Despite this, at the end of the year, spot prices eased, even if at a higher level than the previously, while forward market premium risk ceased, as security of supply was not so alarming anymore. From an economic perspective side, the national energy bill was 115 billion € in 2022, about 70 billion € higher than in 2021, with fossil fuels representing the main cost driver to explain the increase. Electricity imports reached around 7 billion €, because of higher fossil fuel prices and jump of LNG adoption (RTE, 2023).

One year later, security of supply is restored and electricity generation from low-carbon sources increased, while electricity exchange balance became exported-oriented once again. Domestic electricity generation increased by 11% compared to 2022 levels, despite remaining below pre-crisis level. Nuclear fleet availability has been restored to levels comparable to 2014-2019 averages, while wind and solar power constituted 15% of electricity generation and hydropower remained the second-largest electricity source. Moreover, coal-generated electricity felt to 0.17% of French electricity mix, together with a steep decrease in gas generation, that accounted for 30 TWh (-14 TWh from 2022). The electricity consumption downward trend observed in 2022 proceeded throughout 2023, affecting all sectors from businesses to households and public administrations. Analysed from a different perspective, the sharp fall of industrial and residential consumption could reflect a worsening in the macroeconomic situation, characterised by persistent inflation. Furthermore, high temperatures influenced energy gross consumption, a figure that does not consider adjustments for climate effects. This amount reached 438.7 TWh, representing its lowest level since 2002. On the power generation-side, nuclear energy accounted for 320.4 TWh thanks to better availability rates. Wind power generation placed in the third place within the French generation mix, thanks to more installed capacity and good load factors. Delving into nuclear availability, nuclear rate was 63%, equal to 38.6 GW while it was 54% during 2022. Although security of supply was not endangered as in 2022, the nuclear fleet has not returned to its nominal operation. The availability drops in which France incurred in 2022 can be compared with the closure of 14 reactors of 900 MW. Thus, the nuclear programme would require reactors life-cycle extensions to become a lever for achieving industrial objective and supporting a shift towards carbon-neutrality. Hydropower generation instead, was at the second place within the French electricity mix (12% of the total), with water stocks at very high levels, compared to 2022. Variable RES already play an important role for French electricity supply, with wind and solar that had overcome hydropower generation for the second year in a row. Photovoltaic installations, following a rapid pace, with an installed capacity of 3.1 GW and a photovoltaic solar fleet that has reached 19 GW (+3.1 GW from 2022). Conversely, onshore wind power has slowed down its development rate, while offshore wind farms projects are in progress. This renewable acceleration is pivotal to achieve 2030 decarbonisation objectives and climate neutrality by 2050. In 2023, thermal production from fossil fuels decreased by 34% compared to 2022, from 49.2 TWh to 32.6 TWh. Indeed, gas-fired production returned to being at the fourth place of French electricity mix (6% of the

total). Furthermore, coal has virtually been phased out, looking at the minor volumes produced only in the first months of the year (0.8 TWh). The implication for wholesale markets has been a significant drop in electricity prices, from 276 €/MWh in 2022 to 97 €/MWh in 2023. Moreover, the increase in LNG share, allowed the diversification of gas supply, thanks to the construction of temporally regasification terminals. Higher gas stocks level enabled a decrease in average prices, down to 40 €/MWh. Therefore, the reduction of wholesale markets' electricity price could be read a direct consequence of falling gas prices. In addition, France export position has been restored through decreasing energy demand and renewable production growth. During 147 hours of the year, the country experienced negative electricity prices, mainly during summer because of high PV production. In the spring of 2023, France had to deal with risk premium reappearance, after the discovery of new stress corrosion cracking on repaired welds. Electricity prices, returned to be aligned with European average in the winter 2023-2024, although higher and more volatile than before energy crisis. Anyway, French generation mix distinctiveness foster a structural misalignment between market prices and production cost. Indeed, low-carbon production expenditures don't match with gas-powered electricity benchmarks and EU-level market balances. The European electricity market is based on the merit order principle, meaning that the spot price is set hourly by the marginal cost of the last power plant needed to meet demand. During the energy crisis, this mechanism contributed to a sharp increase in wholesale electricity prices, especially when gas-fired plants became price-setting units. This situation pushed EU Member States to ask for a structural reform of the electricity market, then president in March 2023 by the European Commission. The reform promotes instruments such as Contracts for Difference (CfDs) and Power Purchase Agreements (PPAs) to reduce exposure to short-term price volatility. In France, the reform pressures led to a public debate focused EDF revenue redistribution by taxing the income obtained from historical nuclear fleet to protect electricity consumers. The 2023 energy bill has been reduced by 4 billion $€_{2023}$, since France returned to be a net electricity exporter. During the period 2014-2019, energy costs were reduced only by around 2 billion $€_{2023}$ as yearly average, while 2022 energy imports generated an 8 billion $€_{2023}$ increase. In 2023, emissions from electricity generation in France fell to 16.1 $MtCO_2eq$, their lowest level since the early 1950s and 32% lower than in 2022. The long-term decline in coal and fossil fuel generation has significantly reduced the carbon intensity of the French power sector, at 32 gCO2eq/kWh, far below Germany's 303 gCO_2eq/kWh and Italy's 270 gCO_2eq/kWh. Moreover, French electricity

exports helped avoid emissions in these neighbouring countries by replacing more carbon-intensive generation. The European electricity mix is gradually decarbonising, with declining emission intensities in major countries, such as the previously mentioned Germany and Italy. France already benefits from its largely low-carbon electricity mix, but its future challenge is to expand low-carbon electricity production to support sectors electrification, especially transport, industry and buildings. In 2023, emissions linked to French electricity consumption, including imports and exports, fell from 28.4 $MtCO_2eq$ to 15.3 $MtCO_2eq$, mainly due to lower imports and the recovery of nuclear and hydropower generation. This confirms both the strength of the French low-carbon model and its dependence on sufficient domestic nuclear availability (RTE, 2024).

Concerning the beginning of European Pressurized Reactor (EPR) projects, in 2007 French safety authorities found unsatisfactory quality control procedures for Flamanville-3 EPR project. This endeavour was 2 years behind schedule and 1.7 billion € over budget and not conceivable for power export only. Moreover, at the time there were some doubts regarding the ideal generating mix for the country, and the aging of French nuclear fleet was not supporting the implementation of such a program (Schneider, M., 2010). Some years later, EDF presented the EPR2 programme as the central pillar of France's new nuclear strategy and as one of the largest industrial programmes in Europe. EDF plans the construction of six new-generation reactors on three existing nuclear sites: Penly, Gravelines and Bugey and each site is expected to host two EPR2 reactors. According to the company, the objective is to strengthen France's energy sovereignty, support the production of low-carbon electricity and contribute to the long-term decarbonisation of the power system. The first EPR2 reactor at Penly is planned to be operational by 2038, with the following reactors commissioned progressively at intervals of 12 to 18 months. The main project phases include public consultation, regulatory authorisation, preparatory works, building and testing and eventually the gradual commissioning of the six reactors. EDF estimates a final cost of 72.8 billion $€_{2020}$ for the entire EPR2 programme, with strict auditing conducted by the French interministerial delegation on new nuclear. This confirms that the relaunch of nuclear power in France is not only a technological matter, but it also belongs to a broader long-term industrial, financial and political strategy. The fifth French Nuclear Policy Council, held in March 2026 at the Penly site, confirmed the strategic role of nuclear power in France's long-term energy policy. EDF, Framatome, CEA and Orano call for State's commitment to maintain and develop the nuclear sector to guarantee competitive,

sovereign and low-carbon electricity. The Council reaffirmed the central importance of the programme to build six EPR2 reactors at Penly, Gravelines and Bugey, while also confirming the financing principles of the project, subject to European Commission approval. According to the project partners, it will also be fundamental to develop the nuclear fuel cycle alongside the construction of the six new reactors. The expected modernisation pathway should receive support from programmes aimed at the extension of the lifetime of existing treatment. Moreover, the fostering of recycling and the creation of recycled-fuel fabrication facilities, could be achieved through Orano's *Aval du Futur* programme, which is intended to prepare the technologies and infrastructures that will succeed the current La Hague and Melox fuel reprocessing facilities. At the end, the declared Council ambition is to move towards a closed nuclear fuel cycle. To prove this clear engagement, a four-year study phase was launched to design the necessary facilities, including a fast-neutron reactor and the associated fuel fabrication and treatment infrastructures. This confirms that recent French nuclear policy is not limited to electricity generation, but also concerns long-term fuel-cycle strategy, recycling capacity and industrial sovereignty (EDF, 2026). The recent French energy strategy marks a clear reversal compared with the previous objective of reducing the share of nuclear power in electricity generation. The 2015 energy transition law had set the target of lowering nuclear power from around 75% to 50% of electricity generation, an objective later postponed to 2035 by the 2019 Energy and Climate Law. However, the 2023 nuclear acceleration law removed both the 50% nuclear share target and the 63.2 GW cap on authorised nuclear capacity. This shift was further consolidated by the Multiannual Energy Program/PPE3 (Programmation pluriannuelle de l'énergie) which explicitly chooses a nuclear revival strategy. The objective is to obtain a nuclear output of around 380 TWh/year in 2030 and 420 TWh/year in 2035. The PPE3 nuclear target relies mainly on the improved availability and lifetime extension of the existing fleet, together with the commissioning and ramp-up of Flamanville 3. The six EPR2 reactors and the possible additional eight units are instead part of the longer-term strategy for replacing the ageing fleet after 2035. (Ministère de l'Économie, des Finances et de la Souveraineté industrielle, énergétique et numérique, 2026).

As already understood in paragraph 3.1, France's deterrence strategy is nuclear, which aims at protecting the country against aggressions from other states regardless the possible source origin. Only the President of the Republic can approve the use of this weapon in order to guarantee nation's security. The safeguard of national vital interests is deliberately ambiguous,

complicating and discouraging potential aggressive actions. French deterrence includes the possibility of the so-called nuclear warning strike against an aggressor to dissuade him from any further action that could potentially compromise vital interests' safety. Moreover, the deterrence is exercised permanently, and this make it more credible and strategically relevant. France considers its deterrence as a fundamental solidarity instrument, capable to strengthen European defence integration. Indeed, in March 2025, Macron stated that also main partners interests are taken into account to define broad vital interests. Given the nuclear-weapon state condition of France, the country supports NATO's nuclear policy, without joining the organisation of its nuclear planning mechanism. The President of the Republic opened a strategic dialogue to extend French nuclear deterrence to Europe's collective security and common defence. In this framework, NATO's nuclear policy should complement European allies' protection, without overlapping with security objectives provided by French nuclear deterrence. However, the final use decision won't be shared as the President of the Republic of France is the sole individual authorised, who can't envisage any tactical use other than the declared strategic role. France is currently engaged to promote the non-proliferation treaty (NPT) as central theme, together with the importance of nuclear disarmament, though it be still actively mobilised against proliferation crises (SGDSN, 2025). In 2026, European nuclear deterrence structure is undergoing an important transformation, resulting from recent years geopolitical tensions and uncertainties. Specifically, Moscow nuclear threats and the growing concerns around the reliability of US security have prompted nuclear deterrence topic at the center of European defence dialogue. Macron's 2026 so-called "forward deterrence" initiative foresees deeper strategic consultations, joint nuclear exercises between allies and the potential sharing of French nuclear-capable aircraft to protect allied countries. Again, French nuclear decision-making does not incur in any common sharing adjustments to preserve country's strategic autonomy. Furthermore, according to the European Parliament, nuclear deterrence plays a decisive role to guarantee European security, highlighting French and British nuclear forces' role. The two countries together maintained an estimated stockpile of around 515 nuclear warheads in 2025, indicatively 225 in UK and 290 in France, that has also around 80 retired warheads pending dismantlements. For a comparative assessment, the US and Russia lead the worldwide nuclear arsenal ranking by far. The US could count on approximately 3700 nuclear warheads in 2025, while estimates for Russia indicate about 4309 nuclear warheads deployed for strategic and non-strategic country's interests. French nuclear forces include both

submarine-launched ballistic missiles and an airborne nuclear component. France's nuclear capabilities are getting to expand through next-generation nuclear delivery systems. Ultimately, French forward deterrence proposal should gather NATO's effort with EU conventional nuclear military capabilities, including missile warning, air and missile defence and long-range strike systems. This initiative represents a clear attempt to implement the Europeanisation of deterrence without an EU-centralised control over the nuclear arsenals. In this sense, vital interests include neighbouring countries because of political, economic and security interdependence. Most importantly, this process should not be seen as an attempt of establish an alternative to NATO. Instead, its final aim is supporting European security, without compromising NATO's nuclear-sharing arrangements. Geopolitical analysts suggest that French endeavour is the adaptation of its nuclear policy to face a deteriorating EU security (European Parliamentary Research Service, 2026).

IV. Nuclear power in the age of energy transition

4.1 EU governance framework as constraint and opportunity

The 2009/71/Euratom council directive established a community framework regulating the safety of nuclear installations. Its amendment is more focused on the protection of health of individuals as industry workers, the compliance with safety fundamentals and preservation of a clear national framework concerning spent fuel and nuclear waste management. Even though the Union has still actively overseeing the implementation of the directive within the member countries, the conformity and the respect of these principles is a matter of national responsibility. The Directive frames nuclear safety as a lifecycle obligation, covering the siting, design, construction, commissioning, operation and decommissioning of nuclear installations. This strengthens the idea that the role of nuclear power in the energy transition cannot be assessed only through electricity generation, but must also include long-term safety, ageing management and decommissioning. After Fukushima accident of 2011, the European Union has ordered to conduct stress tests of the nuclear power plants to understand the possibility for safety improvements. The accident did not immediately reduce French nuclear generation, but it strongly influenced the European regulatory framework. The 2014 Nuclear Safety Directive was adopted in response to the lessons learned from Fukushima and the EU-wide stress tests, reinforcing the idea that nuclear power could continue only under stricter safety, transparency and risk-management conditions. For the design of new reactors, it will be expected a continue enhancement and application of defence in depth principle. The implementation of this system is essential to guarantee independent safety layers of protection in case of nuclear accident, for instance, while the first level of protection should prevent abnormal operation or technical failures, the last level should mitigate the radiological consequences of significant external releases. Impartiality within nuclear sector is pivotal and represents a key driver in decision-making, therefore national nuclear safety agencies shouldn't be moved by any political, economic or social undue influence. This directive mainly confirmed and strengthened the position of the ASN. France already had an independent nuclear safety authority, but the Directive embedded this model within a binding EU framework requiring effective regulatory independence, transparency, sufficient resources, conflict-of-interest prevention and stronger supervisory powers. Thus, for France, the Directive represented not a radical institutional change, but a European consolidation of the ASN's role. Since 1 January 2025, the French nuclear safety governance framework has been reorganised through the creation of the ASNR,

resulting from the merger of ASN and IRSN, as an independent administrative authority combining regulatory oversight, technical expertise, research, training and public information There are even possibilities of conflict of interests due to former nuclear industry executives that nowadays cover regulatory roles. This rotation is allowed and justified by the specialised nature of the sector and the limited availability of top-level human resources within nuclear sector. In the occurrence of a transnational border's accident, the coordination between national authorities will be fundamental to ensure a rapid and valuable information exchange, by giving support to their respective crisis management systems. Moreover, in order to guarantee policymakers transparency and absence of conflict of interests, the information should be accessible and understandable to the involvement of the general public. This requirement can constrain nuclear projects by increasing public scrutiny, but it can also improve citizenship legitimacy and trust. The cooperation on nuclear safety between Member States can therefore support the achievement of high levels safety objectives covering the entire lifecycle of nuclear installations as well as enhancing the operations transparency and the engagement with European stakeholders. The EU framework does not replace national responsibility for nuclear safety, but it embeds it within a common Euratom framework. This means that France remains responsible for its nuclear installations, while being subject to EU-level requirements on safety, regulatory independence, transparency and peer review. Periodic safety reviews represent one of the most important EU-derived constraints for the existing French fleet. At least every ten years, licence holders must reassess nuclear safety, taking into account ageing issues, operational experience, recent research and international standards. This requirement is particularly relevant for France, where most reactors, were commissioned between the late 1970s and the mid-1990s. The EU nuclear safety framework acts simultaneously as a constraint and an opportunity for France. It constrains the French nuclear sector by imposing common safety objectives, independent regulation, periodic safety reviews, transparency requirements and peer-review mechanisms. However, it also provides an opportunity by strengthening the legitimacy of nuclear power within the European low-carbon transition. By aligning national nuclear governance with EU safety standards and post-Fukushima lessons, France can present nuclear energy not only as a domestic industrial asset, but also as a technology compatible with European requirements of safety, accountability and long-term risk management (Directive 2014/87/Euratom).

The EU framework also constrained the French nuclear model through electricity market liberalisation and competition rules. A clear example is the NOME (New Organization of the Electricity Market) Law, adopted after an agreement between the French government and the European Commission, which introduced the ARENH mechanism. Under this system, EDF was required to sell part of its historical nuclear electricity production to alternative suppliers at a regulated price, fixed at EUR 42/MWh. The objective was to open the retail electricity market to competition while allowing consumers and competitors to benefit from the low-cost output of the existing nuclear fleet. However, ARENH also revealed the tension between the French state-led nuclear model and the EU liberalised electricity market. When wholesale prices fell below the regulated ARENH price, the mechanism became less attractive for alternative suppliers; when market prices rose, it placed financial pressure on EDF by forcing it to sell part of its nuclear production below market value. In this sense, EU-driven market regulation acted as a constraint on EDF's revenue model and on the economic management of the historical nuclear fleet. At the same time, ARENH can also be interpreted as an opportunity within the EU framework, since it aimed to reconcile France's nuclear legacy with European market integration. By giving alternative suppliers regulated access to historical nuclear electricity, the mechanism sought to distribute the benefits of the French nuclear fleet beyond EDF and to strengthen competition in the retail market. More broadly, it shows how nuclear power in France is not governed only by national industrial strategy, but also by European rules on competition, market access and consumer protection. EU sustainable finance rules represent another important dimension of the European framework affecting nuclear power. The Sustainable Finance Taxonomy, adopted in 2020, created a classification system to identify economic activities that can be considered environmentally sustainable, particularly in relation to climate change mitigation. The inclusion of nuclear energy within this framework was highly debated, mainly because of the application of the DNSH ("do no significant harm") criterion to issues such as radioactive waste, radiation protection and long-term safety. Since the Technical Expert Group did not consider itself able to reach a definitive conclusion on nuclear energy, the European Commission requested a scientific assessment from the Joint Research Centre. In 2021, the JRC concluded that nuclear energy could comply with the DNSH criterion, a finding that was largely supported by further expert assessments requested by the Commission. This process shows how EU governance can act both as a constraint and as an opportunity for nuclear energy. On the one hand, the taxonomy does not automatically classify nuclear power as

sustainable without conditions: it subjects nuclear projects to strict technical screening, safety and waste-management requirements. On the other hand, its inclusion within the sustainable finance framework can strengthen the financial credibility of new nuclear investments by allowing them to be considered compatible with EU climate objectives. For France, this is particularly relevant because the renewal and possible expansion of the nuclear fleet require large-scale, long-term capital investment. The taxonomy therefore creates a conditional opportunity: it can support the financing of new nuclear projects, but only if they comply with the EU's broader environmental and safety standards (IEA, 2021).

Taken together, the Euratom framework shows that the European Union does not directly determine whether France should rely on nuclear power, but it increasingly defines the conditions under which nuclear energy can remain politically, legally and environmentally acceptable. The Basic Safety Standards Directive (Council Directive 2013/59/Euratom) places nuclear activities within a broader system of radiation protection, based on justification, optimisation and dose limitation, and covering occupational, public, medical and emergency exposure situations. At the same time, the Spent Fuel and Radioactive Waste Directive (Council Directive 2011/70/Euratom) introduces a long-term sustainability constraint by requiring Member States to manage radioactive waste and spent fuel responsibly from generation to disposal, while avoiding undue burdens on future generations. This is particularly important because long-term storage is not considered a substitute for final disposal, and national programmes must include inventories, milestones, technical solutions, cost assessments and financing schemes. Therefore, the EU framework acts as a constraint by imposing demanding safety, radiological protection, transparency and waste-management obligations. However, it also represents an opportunity: by complying with these standards, France can reinforce the legitimacy of nuclear power as a low-carbon technology embedded in a broader European system of accountability, risk management and intergenerational responsibility.

4.2 Hybrid energy systems and the evolving role of nuclear

In this century, climate change and energy security have emerged as the most important concerns worldwide. The uncertainties are additionally exacerbated by the intermittent nature of RES and growing public and governmental apprehension over the deployment of nuclear energy alone. An attempt to overcome these limitations can be the implementation of hybrid or

integrated nuclear-renewable energy systems. Specifically, they are conceived as a nuclear power reactor coupled with renewable energy generation and industrial processes. Through this configuration, energy systems could gain from better grid flexibility, energy security and optimised return on invested capital. Considering the forecast of a rapid increase in energy demand and consumption, because of rising global population and world economy, overdependence on fossil fuels cannot be the long-term solution for the energy system. Therefore, as legacy sources are unevenly distributed and easily depletable, nuclear and renewables should reduce dependence on crude oil and natural gas, while ensuring better energy security and energy supplies diversification. However, these two promising energy sources have their specific production troubles. Renewable energy is heavily dependent on climatic conditions and geographical location, while the meltdown of reactor is the main risk that can occur for a nuclear power plant. Moreover, waste management lacks the standardisation of clear policies for radioactive materials and stringent compliance for fuel reconversion activity aimed at military purposes. The capacity factor is an average that represents the percentage of time for which a power plant is operating at its full rated capacity, expressed in yearly terms. Solar photovoltaic systems have a capacity factor between 12-19% and onshore wind around 30%. By way of comparison, a nuclear power plant generates electricity with a capacity factor of 60-100%, comparable to a coal-thermal one (70-90%). Despite renewable resources are considered inexhaustible, they are not infinite and they undergo degradation. RES are not always recyclable and worse they could generate environmental hazards without clear waste management guidelines. Instead, the next generation of nuclear reactors may be based on fusion if supported by R&D activities and investments in technological innovations. The formulation of a balanced energy mix should assess and combinate technical, economic and energy security perspectives. Nowadays, an optimal energy mix should be formed by 50% of renewable sources, 30% of nuclear energy and the remaining 20% of natural gas. Suman, S. (2018) analysed a hybrid energy system composed by a SMR and a concentrated solar thermal plant. This system allows for solar heat transferring to nuclear steam to raise the temperature, while thermal energy storage provides continuous superheating. The findings underline that solar superheating can potentially increase nuclear power plant electric efficiency up to around 37.5%. Moreover, solar heat to electricity conversion efficiency reached 56.2%, almost comparable to combined cycle gas turbine plants (CHPs). Furthermore, another possible configuration encompasses an integrated nuclear-wind energy system, operated in a load-following mode. Consequently, the

proposed nuclear-renewable hybrid systems will require complex interconnections and integration, as the single plants components remain the same of the original setting. Hydrogen production therefore could be crucial within this hybrid framework for its many possible uses. For instance, it is possible to recover heat from a nuclear reactor and generate electricity from RES to ultimately obtain high temperature electrolysis. The expected advantages would be the reduction of GHG emissions, the mitigation of global warming and the supply of highly competitive, grid-scalable renewable energy. In addition, through the exploitation of these integrated systems it will be feasible the production of biofuel, synfuel and hydrogen for the transport sector. Additionally, this system helps the avoidance of stressing a specific infrastructure beyond its threshold level in a given timeframe, supporting pricing and procurement control. Overall, the commercialisation of this energy system could lead to faster ROI (Return on Investment), establishing this configuration as an economically attractive option. Nevertheless, the challenges to implement new forms of hybrid energy systems are multiple and diverse, especially on technological, financial and regulatory dimensions (Suman, S., 2018).

In 2001, The Economist claimed that the problem of nuclear power, though cheap to run, was the expensiveness of its construction. Worldwide building costs' increase has been more intense for nuclear power plants than for other energy sources facilities. Nuclear power plants are considered the key replacement for coal-fired power plants, as they don't emit CO_2 directly and very little indirectly. Nevertheless, even non-nuclear cheaper and faster technologies could substitute the production from fossil fuels. For instance, wind or recovered-heat industrial generation and end-use efficiency cost far less than nuclear energy per kWh, and consequently they save more carbon per dollar. An assumption for too costly new nuclear is that one dollar invested on it, generates a worse effect on climate than spending one dollar on new coal power. Utilities must install 15% reserve margin of extra capacity ready for instant use, and heavily nuclear-reliant areas could not ensure it due to increasing drought risks or earthquake occurrences. Another nuclear plant disadvantage is the mandatory shut down in case of power failure for safety reasons, which imply a long restarting phase. The vulnerability of nuclear transmission lines could make more frequent the happening of regional blackouts. Instead, a portfolio composed by smaller nuclear units could be more reliable, because of its diversity and dispersion complicate failures probability. Moreover, low-carbon competitors to nuclear power, especially distributed generation and efficiency measures, can be deployed more rapidly and

with lower financial risk. This perspective challenges the idea that nuclear power should be considered the only large-scale alternative to fossil fuels. Therefore, nuclear energy future role should be interpreted less as an isolated baseload source and more as one possible component within a broader low-carbon portfolio. Applied to the French case, this means that nuclear power remains relevant as a firm low-carbon source, but its evolving role depends on its ability to operate within a more flexible and diversified electricity system (Lovins, A. B., et al., 2010).

The transformation of electricity system towards a low-carbon, secure and diversified one should look at the evolving role of nuclear power to boost energy mix improvement. Nuclear power has increasingly been framed as a clean and secure energy source, mainly because of its potential contribution to climate mitigation and energy security. Nuclear power must be integrated into wider energy systems that also include renewables, grid flexibility, storage and demand-side management, which answer to growing electrification needs. In this sense, nuclear energy is moving from a traditional baseload function towards a complementary role within hybrid low-carbon systems. IAEA underlined that nuclear energy requires a 100-year commitment to cover all its phases, from development to decommissioning. The agency estimated an average time lapse of 15 years between a decision concerning nuclear energy policy and the first operating power plant. In developing countries these implementation policies would be more efficient through the construction of reactors of small and medium sizes, respectively from 300 MWe to 700 MWe to be suitable for limited electrical grids. Conversely, large reactors may not always be suitable for smaller or less flexible electricity grids, where excessive additional capacity could result in grid stability issues. Therefore, smaller reactor sizes which may be more adaptable to hybrid energy systems and more compatible with decentralised or flexible electricity networks (Squassoni, S., 2010). In the European framework, nuclear energy has become part of the green taxonomy, because of considered as an energy source that could prevent climate change adverse effects. France is playing a supportive role to relaunch nuclear energy within the energy transition context, extending its effort also at European level. According to the green taxonomy provisions both nuclear energy and natural gas can foster EU's decarbonisation and mitigate climate change. Given its low-carbon emissions, nuclear energy has been introduced among the sustainable activities included in the Regulation 2022/1214 of the European Commission. In 2023, during the 65th European treaty anniversary, EU Member States have discussed the inclusion of all accessible and non-fossil energy sources that can support the achievement of climate neutrality by 2050. Supporting

countries argued that nuclear energy can provide up to 150 GW of capacity by 2050 to the European Union, compared to the current level of approximately 100 GW. New nuclear projects, like SMR could allow EU to maintain the 25% level of electricity produced via this energy source. Among the European countries with the most developed nuclear technologies, Finland and France have the lead. In April 2023, Finland started the operations of the so-called *Olkiluoto 3,* which represents the largest reactor in all of Europe, going against the recent European denuclearisation trend. In France, even before the nuclear matter's comprehensive regulation, the energy planning law 781/2005 set French energy policies, promoting the reduction of GHG emissions and climate change prevention. After Covid-19 crisis, the French government created the so-called "*France Relance*" plan, an exceptional 100 billion € programme aimed at boosting nuclear sector cohesion, strengthening technological core competences and fostering economic competitiveness. Furthermore, the plan also encompasses nuclear waste management and climate protection. This ambitious pathway presents projects like *Cigéo,* a deep geological disposal infrastructure that could host radioactive materials at 500 meters depth. This facility should contain around 85 000 m^3 of nuclear High-Level and Intermediate-Level Long-Lived waste. In 2022, Macron declared the country's willingness to complement nuclear relaunch, with a planned solar extension by ten times, the doubling of onshore wind and the construction of 50 offshore wind farms. Nuclear pivotal role is visible in the reactor lifecycle extension decisions and the planning of six new EPR 2, the ultimate generation of nuclear power plants. However, this nuclear acceleration has received some critics from French environmental-oriented political parties which argue the possible weakening of environmental safeguards. Indeed, these nuclear policies could breach the principle of environmental non-regression. Consequently, the implication for the creation of new environmental law should be the preservation of the level of protection already achieved. However, energy policymakers considered these measures necessary to accelerate nuclear deployment, strengthen energy sovereignty, reduce dependence on fossil fuels and contribute to climate neutrality. Therefore, the final decisions should consider both the legal dimension of environmental standards safeguard and the need of more efficient and timely low-carbon solution for French energy infrastructure (Colella, L., 2023). The achievement of climate neutrality is planned every five years through the revision of the National Low Carbon Strategy (*Stratégie nationale bas carbone*).Through the implementation of this net-zero framework, it is possible to explore different policy scenarios that could enable the achievement of climate

neutrality objectives. Ideally, on the demand side, final energy consumption should be reduced by 40% within 30 years, bringing back energy consumption to late 1960s levels. On the other hand, energy supply should rely on decarbonised electricity and domestic biomass production, excluding green gases and decarbonised fuels adopted by other EU countries. Along with carbon neutrality, France has decided to shift towards a system which will guarantee national sovereignty. These developments should be followed by an increasing energy system electrification. In the near and medium term (2030-2035), the increase of decarbonised electricity generation could be achieved if current nuclear fleet will be operating and complemented by RES development. Instead, over the longer term (2050-2060), the decommissioning of II generation reactors and the progressive phasing out of nuclear energy would it translate in an industrial constraint. In absence of nuclear, French generating fleet should be able to replace the 380-400 TWh of annual production capacity of this energy sources, while trying to boost electricity consumption to comply with low-carbon objectives. French energy transition will require structural changes in the transmission network, especially when handling the integration of more renewable energy share within the energy mix. In 2019, 33 billion euros have been announced to be invested over 15 years to modernise the national grid to accommodate the mix approved in the Multiannual Energy Plan. The first step encompasses the renewal of outdated infrastructures, often built after the Second World War. The successive changes will be carried out in accordance with the oldest grid components dismantling and the electricity mix evolution. The integration of non-dispatchable variable generation is expected to require a 61 billion € investment necessary for grid upgrading. The future French electricity system is presented around two main scenarios: the development of systems based exclusively on renewables and systems combining renewables with new nuclear reactors. RTE, the French Transmission System Operator (TSO) stresses that the debate should not be reduced to a simple opposition between the two options, because all scenarios require a power system fundamentally different from today's, with a high share of variable renewables, significant flexibility needs and major investment requirements. Nuclear revival scenarios include the construction of new EPR2 reactors and, in the most ambitious cases, the possible deployment of SMRs. However, RTE also notes that France does not currently have the capacity to build nuclear reactors at the same pace as during the 1980s. The report concludes that new nuclear reactors can make economic sense, especially if they allow France to maintain a nuclear fleet of around 40 GW in 2050. This is because scenarios with a very high share of renewables

require substantial additional costs for flexibility, storage, backup plants and grid reinforcement. Once these system costs are included, scenarios combining renewables and new nuclear appear more competitive in several configurations. Nevertheless, their competitiveness remains highly dependent on financing conditions, since nuclear power is capital-intensive and sensitive to the cost of capital. At the same time, the future system will necessarily become more hybrid and flexible. Whatever the decision on new nuclear, France will need to expand renewables, reinforce the grid, develop interconnections, increase demand-side management, use hydropower storage and deploy batteries to support solar generation. In scenarios with limited nuclear revival or 100% renewables, additional thermal plants fuelled by decarbonised gas or hydrogen would also be required to guarantee security of supply during periods with low wind and solar output. Consequently, atom power future exploitation will include a more diversified low-carbon electricity system combining nuclear, renewables, flexibility, storage, hydrogen and stronger networks. Overall, the recent French programme marks a shift from a debate focused on reducing the nuclear share towards a more pragmatic strategy centred on maintaining low-carbon electricity production, securing energy sovereignty and preparing for the replacement of the ageing reactor fleet. Nuclear power is therefore expected to remain an important pillar of the French transition, but not as a stand-alone solution. Its future contribution will depend on the successful extension of existing reactors, the feasibility of new EPR2 and SMR deployment, the acceleration of renewables, and the ability of the grid to integrate a more flexible and hybrid energy system (RTE, 2021).

Climate change can have a negative effect on energy and power sector, because of the intensification of events like droughts, heatwaves and cold waves. Nowadays, outages are principally caused by these extreme events that are likely to increase in the next years. In the long-term, for worldwide nuclear fleets this could mean an average annual energy loss between 1.4% and 2.4%. Collet et al. (2025), through the adoption of EURO-CORDEX (European Coordinated Regional Climate Downscaling Experiment) framework and EDF historical data concerning power plants outflow temperature, analysed the probability of future outages in France, generated by certain environmental constraints. Considering 2050 time-horizon, they discovered a clear upward trend in stream temperature of Reuse and Garonne rivers, which host two French riverine power plants. For both the facilities has been discovered a +2% upward trend in power outages occurrence, representing around 6 days/year of loss production in full power equivalent days (FPED) terms. The increasing frequency of extreme weather conditions

impacts the cooling of reactors and reduces the overall thermal efficiency. Furthermore, nuclear energy production could be limited by more binding regulation and stringent environmental compliance over riverine and marine ecosystems matters. Anyway, the temporary shutdown of a nuclear power plant can become a time for saving fuel and delaying the planned refuelling, as an attempt to adapt electricity production with broad climate uncertainties (Collet et al., 2025).

The transition to carbon-neutral energy can be achieved through advanced nuclear, complementing renewables expected replacement of fossil fuels technologies. Recycling nuclear waste produced by legacy power plants could serve to provide free fuel for advanced reactors. Compared to renewables, nuclear shows the advantage of a lower life cycle carbon footprint, but it presents the disadvantage of long-lived nuclear waste. Advanced nuclear generates a much smaller amount of nuclear waste, around 1% of the quantity produced by legacy nuclear. The main differences between legacy and advanced reactors are a huge gain in safety, a reduced decay time for nuclear waste and an increased thermal efficiency. According to Rehm, T. (2023) nuclear would be a better choice than solar and wind on both land requirement basis and consumer cost basis. Renewables exploitation faces planetary mineral resources constraints and the social impact of mining, together with the management of end-of-life equipments. In addition, renewables variability, energy storage dependence and important land requirements are not competitive against the fact that nuclear power plants can operate anywhere. Theoretically, given the current global energy demand level, advanced nuclear could provide 9,000 years of renewable energy, while legacy nuclear waste would become fuel for new generation reactors. In this context, thorium reactors and molten salt reactors represent two promising innovative technologies, although they are characterized by the risk of corrosion for structural materials exposed at high temperature. Moreover, crude oil and natural gas could be potentially replaced with nuclear biorefining to produce feedstocks within chemical manufacturing sector. Biomass would be consolidated and stored anaerobically, and then nuclear energy could supply biorefineries with electricity, process heat and hydrogen, increasing efficiency and final output level (Rehm, T., 2023). The endorsement of green technologies aimed at sustainable development would be less effective without implementing a clear environmental regulation framework, composed by policies for CO_2 abatement and environmental taxes. Nuclear energy can contribute to climate change mitigation and the promotion of sustainable development. Although nowadays the transportation sector is largely

dominated by fossil fuels use, nuclear energy could potentially powering trains and vehicles through its carbon-free electricity production. Despite it can support fossil fuels phasing-out and curb GHG emissions, on the other hand, it poses environmental contamination risk and the management of long-term radioactive hazards. Furthermore, nuclear energy displays some critical issues, especially in terms of environmental concerns, nonetheless it is also widely acknowledged as a low-carbon energy source. Therefore, a nuclear widespread adoption can boost the share of low-carbon energy in the national energy mix. According to Zheng, S. et al. (2024), nuclear energy production impacted the sustainable development of the top 17 nuclear energy generating countries between 1995 and 2021. During this time span, nuclear power played a fundamental role in mitigating climate adverse change and supporting sustainable development. This positive association implies that nuclear power decreases a country's dependence on fossil fuels imports, consequently enhancing energy security. Strategically, this means a reduced exposure to energy supply disruptions and price volatility, increasing both the overall environmental and economic performance. Finally, nuclear energy streamlines the transition to a greener industrialisation and modernisation through its reliable electricity production, ultimately supporting industrial growth, infrastructure development and urbanisation (Zheng, S. et al., 2024).

4.3 SMRs: EU push, realistic timelines and sustainability claims

According to the IAEA, the global interest in SMRs is rising because they can produce baseload and dispatchable electricity to foster electricity sector decarbonisation. The key reasons to deploy these new nuclear technologies in the nations' energy mix are the possibility to have flexible power generation and the replacement of aging fossil-fired units. SMRs would be very suitable for niche markets where large reactors or remote grids could not represent the optimal solution for electricity generation. Their minor carbon footprint and flexible siting make them an important energy solution in embarking nuclear power countries and for regional and industrial clusters, thanks to their modularity feature. Furthermore, SMRs are envisioned to decarbonise marine propulsion and making global shipping greener and more sustainable. Nonetheless, some technical issues need to be addressed to streamline the applicability of existing codes and standards, fuel supply management and fuel cycle back-end solutions. Although the promised low upfront capital cost per unit, SMRs economic viability is yet to be proven. SMRs are not a single reactor type, but a broad technological family. The IAEA

identifies several SMR categories, ranging from water-cooled reactors to gas-cooled, molten salt, liquid-metal fast-neutron and microreactor designs. This technological diversity reflects the different potential applications of SMRs, from electricity generation to industrial heat, marine use and small-scale or remote energy supply. Among the SMRs already in operation, in the Russian Federation there are two reactors of 35 MWe each, while in China two reactors linked to a single turbine generate 200 MWe. In France, the development of SMRs is carried out through the France Relance 2030 funds. French endeavour includes the EDF-NUWARD SMR, which is also a Pressurized Water Reactor (PWR), and nine other advanced designs.

Family of SMRs technologies	Type of SMRs	Number of designs/projects
	Land-based, water-cooled	14
	Marine-based, water-cooled	6
	Gas cooled	14
	Microreactor	13
	Molten salt	11
	Liquid-metal, fast neutron	10

Table 4.1: Number of SMR designs worldwide by technology family

The design of future SMRs and the operations of the existing ones can benefit from legacy nuclear lesson learned in fuel supply, spent fuel, waste and decommissioning management. However, advanced reactors designs should include new fuel concepts that require the construction of specific facilities. Fuel cycle decisions are usually determined by governments that could impose significant restrictions on nuclear fuel supply chain. These innovative fuel cycles are composed by Th/U-233, reprocessed uranium (RepU), MOX and transuranic fuels. Many SMR designs require high assay low enriched uranium (HALEU) fuel to operate, which is uniquely produced in the Russian Federation on a commercial scale. For that reason, interested countries are enhancing their production capacity to ensure sufficient HALEU availability on the market. SMRs sustainable development and deployment can be obtained only through an effective nuclear spent fuel and radioactive waste management. The adoption of a selected approach will therefore depend on countries' existing infrastructure and management plans. Like other energy production technologies, SMRs can be evaluated using the LCOE metric to assess the MWh or kWh cost of building and operating a plant. In particular,

5 GW of SMRs capacity gives a LCOE threshold comparable with a larger nuclear power plant. Moreover, some new generation designs allow flexible operation, load-following production, providing key services to alleviate pressures on grids. On the financing side, the modular nature of SMRs could offer the opportunity for phased investments, improving overall projects attractiveness for investors. Project fund raising should include financial mechanisms, such as green and transition bonds, while secure source of income could be obtained through power purchase agreements (PPAs), contracts for difference (CfD) and the regulated asset base (RAB) as revenue models. Nuclear power projects contribute to generate long-term economic growth, by generating positive impacts on national economies. More specifically, SMRs can support the replacement of obsolete energy infrastructure, therefore contributing to overall economic growth. By way of example, a Canadian study on five 300 MWe SMRs is projected to generate a positive impact on GDP of CAN$ 17 billion over 65 years. Even in countries that do not have a so well-established manufacturing and construction experience, SMRs would represent a strategic solution to improve grid reliability and resiliency. Finally, the potential SMRs end-users could be data centres, as well as AI and cryptocurrencies networks of the major tech companies, as they necessitate of continuous and stable electricity supply to run their businesses. Indeed, these companies need to decarbonise their operation and achieve their sustainability goals. In this context, SMRs can compete with renewables variability and storage requirement issues. The best scenario would encompass the deployment of modular, micro or scale nuclear to power energy intensive companies, after raising private capital for the nuclear technologies' development stages. Among the other feasible application for SMRs it’s important to highlight cogeneration, district heating, industrial heat, desalination and hydrogen production. Alternatively, a SMR can be also become part of a hybrid energy system, where it would be coupled with energy storage components and electricity production from renewable energy sources (International Atomic Energy Agency, 2024)

EU industrial competitiveness and decarbonisation objectives can be achieved only through the supply of homegrown, affordable and clean energy that ultimately fosters energy security and independence. The fulfilment of EU policy objectives could benefit from the support of the emerging category of nuclear reactor known as Small Modular Reactors (SMRs). They can ensure the highest safety and security standards, together with radiation protection. Because they are smaller in size and output, compared to legacy nuclear power reactors, they can be transported to a site either for starting operations or for assembly because of their modularity

feature. There are light water SMRs, typically developed from incumbent water-cooled nuclear reactors, Advanced Modular Reactors that use innovative concepts (AMRs), next-generation with different cooling systems (Generation IV) reactors and Microreactors which produce less than 10 MW of electric power, with long refuelling cycles and transportable. Preliminary European Union estimates indicate that SMRs capacity is expected to range from 17 GW to 53 GW by 2050 for electricity generation and heat, hydrogen and other fuels production. In this way, SMRs could support a more sustainable energy mix and a more effective grid load balancing. This technology could be useful for hard-to-abate industrial and residential energy purposes, by focusing on clean electricity production. Alleviating the pressure on electricity grids should be a fundamental objective to achieve, as well as answering to Energy Intensive Industries (EIIs) and data centres growing demand, while supporting hydrogen production and water desalination. Moreover, microreactors could be adopted for broad industrial and infrastructural uses, given their portability and economic scalability. Data centres in Europe currently account for around 70 TWh of electricity consumption, a figure that could reach 115 TWh by 2030. SMR co-location with data centres may reduce grid congestions and avoid costly upgrading necessary for these facilities. European vision for the development is clear and encompass a comprehensive shared industrial project, where collaboration in research, financing and licensing is pivotal to complete this endeavour. Conversely, a fragmented approach could undermine manufacturing capacity, public confidence and future investments. Project competitiveness and profitability will result from cooperation among EU countries and reduced time-to-market. An important market driver would be the increasing electrification and decarbonised production for an efficient SMRs deployment. A proper SMRs industrial value chain should foresee the first-of-a-kind installations no later than 2030s, while EU regulatory authorities should enable timely licensing and ensuring safety and environmental standards compliance. In September 2025, the Strategic Action Plan was presented by the European Industrial Alliance on Small Modular Reactors to deliver on time and on budget an actionable industrial program. This planning includes a limited number of projects, identifying opportunities for the development of light water small and modular reactors (LW-SMRs) and advanced modular reactors (AMRs). It will be pivotal to strengthen the partnership with technology holders, who often have at their disposal the most advanced LW-SMR prospects, though outside EU. Indeed, in December 2025, United States Department of Energy announced USD 450 million for SMRs licensing, together with USD 900 million granting to support

deployments of Generation III+ SMR projects. Also, Canada funded SMRs commitment, raising approximately CAD 3 billion, while the first SMRs operating are located in China and Russia. At European level, the Euratom Research and Training Programme of 2021–2025 boosted innovation, testing and construction of demonstration facilities for AMRs. The European supply chain should generate added value throughout the implementation phases of SMRs, especially in accordance with REPowerEU objectives of better fuel cycle services, such as enrichment and conversion. Furthermore, the development of modular manufacturing would allow shorter construction times, making European industry more competitive than in the past. Despite, the historical nuclear industrial experience within Europe, the continent supply chain necessitates a strong revitalisation action plan to avoid imports path dependence for new builds and the supply of SMRs components. Therefore, SMR technology developers, utility companies and potential end-users can boost market demand, only through a close collaboration in every value chain step. SMR start-ups and scale-ups joint effort and collaboration could be fundamental to bring projects to the prototype stage. Most importantly, a fuel production and reprocessing common direction is vital to avoid economic inefficiencies deriving from unbundled development of different fuel cycles and waste management strategies. Even projects focused on diverse reactor design should exploit scope economies and benefit from a collective effort. The SMR business model is based on reduced construction time compared to large-scale nuclear power plant and it requires fewer initial investments due to facilities' dimension. In turn, this enables a lower overall financing cost per unit, fostering SMRs attractiveness for potential investors. Building additional reactor modules in sequence represents an economic strategy aimed at revenues generation before the completion of the entire plant. Nevertheless, on the practical side, this business model heavily relies on the achievement of modularity and serial production. EU Member States that are willing to include SMRs in their long-term energy policies are called to develop de-risking financing instruments, under CSRD (Corporate Sustainability Reporting Directive) to leverage transparency for stakeholders. The IPCEI (Important Project of Common European Interest) could pool resources to boost research, development and innovation of such technologies, enabling the mobilisation of private capital. Instead, the Net-Zero Industry Act (NZIA) could streamline access to finance, reducing permitting time and supporting strategic new generation reactors projects. Indeed, under this NZIA framework, Member States and EU regions could create ad hoc *SMR Valleys* for the manufacturing and assembly processes. Industrial actors could co-

invest in SMR projects, particularly in sectors such as battery gigafactories, AI data centres and large computing hubs, which may become future SMR users. Tripartite agreements between off-takers, nuclear developers, supply-chain firms and Member States could support the reduction of financial risk associated and eventually accelerate deployment. At the same time, EU instruments such as the Startup and Scaleup Strategy, the European Innovation Council and the Scaleup Europe Fund are intended to support innovative nuclear start-ups and mobilise private investment in strategic nuclear technologies. Public policy support will be necessary for the development of the SMRs ecosystem, specifically to overcome economic and regulatory barriers. Euratom Research and Training Programme for the period 2026-2027 is expected to be funded with EUR 15 million to proceed further research on the SMRs safety. In addition, for the 2028-2034 multiannual financial framework, EU Commission indicated an increase in economic resources within nuclear energy area. Moreover, the SMR ecosystem required skilled and competent workforce to ensure the safe use of nuclear technologies in the European Union. Recently, the European Nuclear Safety Regulators' Group (ENSREG) has established a dedicated task force to exchange key information on designs before the SMRs licensing phase. This pre-licensing coordination effort should guarantee resources saving, speed-up of procedures and avoidance of duplication. Ensuring public awareness and understanding of SMRs development initiative could be pursued through transparent communication and stakeholders' engagement. Lastly, SMRs can potentially contribute to the transition of EU economy towards the first climate neutral one, by strengthening its strategic autonomy and energy independence. The realistic deployment target is early 2030s, even if the success of these projects will depend on access to capital, technical knowledge sharing, research funds and infrastructural enhancements (European Commission, 2026).

Conclusions:

The objective of this thesis was to assess whether nuclear power has been a sustainable choice for French long-term energy security. The analysis was conducted through a threefold approach to sustainability. It encompassed the economic sustainability of the French nuclear program, the environmental sustainability through the monetisation of its ecological impact and the political and strategic sustainability of one of the largest national nuclear commitments worldwide.

Nuclear energy is considered a low-carbon energy source, especially in the electricity generation phase. However, its environmental sustainability is largely dependent on plant construction, fuel cycle and the broader impacts of radioactive waste managements. The radioactive waste generated during nuclear power plants operations represents only 5% of the total waste amount. Moreover, the adoption of a Circular Economy (CE) framework and its integration with a Life Cycle Assessment (LCA) approach could streamline environmental impacts measurements. According to the literature, the increase of nuclear energy consumption by 1% leads to a reduction of production-based CO_2 emissions of 0.07%, showing a weak nuclear effect on the comprehensive carbon footprint. In France, the energy sector has an average carbon intensity of 56.9 gCO_2eq/kWh, with nuclear power generation producing 3.7 gCO_2eq/kWh, making French electricity mix one of the least carbon-intensive in Europe. In addition, the life-cycle assessment of EDF indicates a nuclear energy direct water consumption of 1.3 L/kWh, while cooling systems choice affects water withdrawal volumes. Although, of the total amount of water used during operations only 3.7% is unrecoverable, nuclear energy production is expected to require 128.3 bcm (billion cubic metres) worldwide by 2030. Considering a growing water demand within the energy sector, up to 400 bcm in less than five years, nuclear would be accountable for 32% of the consumption. A part of the literature argues that a 1% increase in nuclear consumption is correlated with a 0.30% increase in carbon emissions. This could be partly explained by the existing nexus between general economic growth and carbon emissions surge. Indeed, nuclear energy CO_2 emissions are comparable to those of wind power, and it's far below the other energy sources' alternatives. Differently, some studies suggest that a reduction of CO_2 emissions level by 1% would require a 3% increase in nuclear energy, while a 5% increase would be necessary for renewable energy sources to compensate the same effect. Consequently, nuclear phasing-out could induce an augmentation of environmental and financial CO_2 -related costs. Furthermore, the French nuclear has very

few impacts in relation to per capita CO_2 emissions, equal to 4.32 tonnes/inhabitant. On the other hand, in France, the cost of storage for High-Level Long-Lived radioactive waste corresponds to some hundreds of €/MWh, underlining a non-negligible effect on both French economy and environmental quality. The monetisation of nuclear life-cycle emissions further illustrates the limited climate externality of French nuclear power. Using a life-cycle intensity of 3.7 gCO_2eq/kWh and French nuclear generation of 373 TWh in 2025, total emissions correspond to around 1.38 million tonnes of CO_2 equivalent. With a carbon value of approximately 86–87 €/tCO_2, aligned with EU ETS allowance prices, the monetised climate externality is around EUR 119–120 million, or only 0.32 €/MWh. This confirms that the climate-related external cost of nuclear electricity remains very low compared with the overall generation cost. However, this does not include other environmental and institutional costs, especially those linked to waste, decommissioning, long-term storage and water vulnerability.

In 2010, EDF estimated an initial construction cost of 72.9 billion $€_{2010}$, which reached 83.2 billion $€_{2010}$ adding pre-exploitation expenses. In addition, nuclear electricity research in the period 1957-2010 accounted for 55 billion $€_{2010}$, equal to a 1 billion $€_{2010}$ annual average. Overall, the amount of the past investments for the development of the current nuclear fleet corresponds to 188 billion $€_{2010}$. Moreover, the expenses for High Level Long-Lived and Intermediate-Level Long-Lived waste were approximately 22 billion $€_{2010}$. Nowadays, French nuclear average generation cost is 60.3 €/MWh, with fuel expenses ranging from 6 to 9 €/MWh. Nuclear energy bears the lowest expected cost among the other energy sources alternatives. Nuclear power plants are more affordable than legacy coal-fired plants and they can be more cost-effective against Combined Cycle Gas Turbines (CCGTs). The LCOE of historical French nuclear ranged between 59 and 83 €/MWh. A 20-years lifetime extension for the existing nuclear facilities long-term operation (LTO) would require 8.25 USD/MWh, while decommissioning would cost around 35 USD/MWh. Thus, retrofitting measures could be more effective the construction of new nuclear plants or dismantling decisions. In every case, the projected overnight cost for new nuclear is 4000 USD $_{2018}$/kWh, corresponding to a 20% cost reduction from 2010 (5000 USD $_{2018}$/kWh). Nonetheless, construction time delays and budget overruns could lead to rising cost, as for the French Flamanville 3 unit that suffered a steep increase in the annual construction cost, from 1,886 USD/kWe to 8,620 USD/kWe. The overnight cost could be reduced through a more standardised and efficient reactor design, that would decrease the perceived investment risk. For this reason, the *Grand Carénage* programme

and the periodic safety reviews of the existing fleet are not only technical measures, but also key instruments of economic and strategic sustainability.

The quantitative analysis of electricity prices provides an additional perspective on the economic role of nuclear power. The comparison of average household electricity prices between 2007 and 2025 shows that France and Finland recorded the most competitive values among the selected countries, around 0.17 €/kWh, while Germany reached about 0.29 €/kWh, Italy around 0.24 €/kWh and Spain around 0.22 €/kWh. This does not prove that nuclear power alone causes lower prices, but it suggests that countries with a significant nuclear component may benefit from lower exposure to fossil-fuel price volatility, especially during periods of energy crisis. Moreover, the relationship between nuclear share and household electricity prices shows a moderate negative correlation, with a coefficient of $r = -0.54$. This means that, in the selected panel of countries and years, a higher nuclear share tends to be associated with lower household electricity prices. The French case is particularly consistent with this pattern, since France maintained a very high nuclear share, generally between 65% and 80%, while keeping household electricity prices comparatively moderate for most of the period analysed. The findings for non-household electricity prices are almost the same, as the correlation coefficient is $r = -0.53$. This is especially relevant for industrial and business consumers, because electricity prices directly influence production costs and industrial competitiveness. In this case too, France and Finland are positioned in the lower-price area, while Germany and Italy occupy higher-price positions. The result suggests that nuclear power may contribute to industrial price competitiveness by limiting exposure to fossil-fuel volatility and supporting the supply of cheaper domestic electricity. However, the relationship remains descriptive rather than causal, since non-household prices are also affected by taxation, network charges, market design and national regulatory choices.

The tax-excluded analysis further confirms the need for caution. When taxes and levies are removed, the correlation between nuclear share and household electricity prices remains negative, but becomes weaker, with a value of $r = -0.43$. This highlights that the relationship between nuclear power and electricity prices is not explained only by taxation differences, but also that nuclear share alone cannot account for all price dynamics. Finland, for example, shows that a higher nuclear share may coexist with rising tax-excluded prices, while France follows the expected pattern more clearly. Therefore, the price analysis should be interpreted as a pooled

descriptive correlation: it partially confirms the hypothesis that nuclear energy can contribute to price moderation, especially in France, but it also shows that electricity prices depend on a wider set of variables, including fossil-fuel dependence, gas prices, renewable availability, network costs and regulatory frameworks.

Finally, the strategic and political dimension is essential to answer the research question. The French nuclear programme was not only an energy project, but also a state-led strategy of sovereignty. From the post-war period onwards, nuclear power was connected to national independence, technological primacy, industrial policy and military autonomy. Institutions such as the CEA and EDF created an integrated nuclear system capable of linking research, reactor development, fuel-cycle activities, electricity production, safety governance and waste management. This institutional continuity explains why France was able to build a large nuclear fleet and maintain a unique position in Europe. The long-term strategic value of nuclear power became especially visible during energy crises. The oil shocks of the 1970s strengthened the political justification for the Messmer Plan, while the recent gas and electricity crises confirmed the importance of domestic low-carbon electricity. In 2024, nuclear power accounted for a major part of domestic primary energy production and contributed to the recovery of France's energy independence rate, which reached 60.7%, its highest historical level. This confirms that nuclear power remains central to French energy sovereignty, although its contribution depends strongly on reactor availability, maintenance performance and long-term fleet management. At the same time, the 2022 nuclear availability crisis showed the limits of excessive dependence on a single dominant technology. When several reactors were unavailable because of stress corrosion, maintenance delays and the consequences of Covid-19, France temporarily lost part of its low-carbon advantage and had to rely more on gas-fired generation and electricity imports. This episode demonstrates that nuclear power strengthens energy security only if the fleet remains technically reliable, financially supported and institutionally well-managed. Therefore, strategic sustainability does not mean relying exclusively on nuclear power, but ensuring that nuclear generation is integrated within a diversified system including renewables, grid reinforcement, interconnections, storage, demand-side management and flexibility. This is also the main implication of recent French and European developments. The EPR2 programme, the PPE3 orientation, the renewal of the fuel cycle and the EU push for SMRs show that nuclear power is expected to remain part of the future energy system. Nevertheless, nuclear power can no longer be interpreted only as traditional baseload electricity. It is increasingly expected to

operate within a hybrid low-carbon system, where firm nuclear generation coexists with variable renewables, storage, hydrogen production, industrial heat demand, data centres and stronger electricity networks. SMRs may offer future opportunities in this direction, but their real contribution will depend on licensing, financing, supply-chain capacity, standardisation and realistic deployment timelines.

In conclusion, this analysis shows that nuclear power has been a sustainable choice for French long-term energy security, though only under specific conditions. It has provided France with low-carbon electricity, reduced dependence on imported fossil fuels, supported energy sovereignty and contributed to price moderation compared with countries more exposed to gas and coal. However, this sustainability is not automatic. It depends on the capacity to control costs, manage radioactive waste, secure water resources, extend the existing fleet safely, finance new projects and integrate nuclear power within a more flexible and diversified electricity system. The French case therefore confirms that nuclear energy is neither a perfect solution nor an obsolete technology. It is a historically constructed strategic asset whose future sustainability will depend on political stability, industrial coordination, technological reliability and its capacity to support the broader transition towards a secure, low-carbon and economically resilient energy system.

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