ELOI MICHEL MARIO GUISNET

The French electricity sector in the energy transition

PROJETO DE GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO APRESENTADO AO DEPARTAMENTO DE ENGENHARIA INDUSTRIAL DA PUC-RIO, COMO PARTE DOS REQUISITOS PARA OBTENÇÃO DO TÍTULO DE ENGENHEIRO DE PRODUÇÃO

Orientador: Fernando Luiz Cyrino Oliveira

Co-Orientador: Gustavo de Andrade Melo

Departamento de Engenharia Industrial

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Resumo:

Juntamente com a União Europeia, a França se envolveu em uma transição energética com o objetivo de descarbonizar completamente a economia até 2050. O setor de eletricidade desempenha um papel importante nessa transição. Este trabalho busca analisar o setor elétrico francês, descrevendo sua história, características físicas e mercados de eletricidade, para entender quais mudanças são necessárias para a transição e como essas mudanças serão implementadas até 2050. No curso deste trabalho, discutimos os aspectos importantes dessa transição energética. Esses aspectos são um forte desenvolvimento de energias renováveis, uma reestruturação da rede que permita integrar essas energias renováveis e atender à nova demanda de consumo (carro elétrico, eletrificação da indústria, produção de hidrogênio), bem como uma reforma dos mercados de energia, tornando-os mais adaptados aos desafios da transição. Está claro que a França tem muito a se adaptar para atingir o objetivo de carbono zero até 2050, mas as soluções existem e essa transição energética é totalmente possível do ponto de vista do setor elétrico.

Palavras-Chaves:

Transição energética, Setor elétrico francês, Renovável, Rede elétrica, Mercados Europeus de eletricidade

Abstract:

Together with the European Union, France is committed to an energy transition aimed at completely decarbonizing the economy by 2050. The electricity sector plays a major role in this transition. This study seeks to analyze the French electricity sector, describing its history, physical characteristics, and electricity markets, to understand what changes are necessary for the transition and how these changes will be implemented by 2050. In the course of this work, we have discussed important aspects of this energy transition. These aspects are a strong development of renewable energies, a restructuring of the grid allowing to integrate of these renewable energies and to respond to new consumer demand (electric cars, electrification of industry, hydrogen production), as well as a reform of the energy markets making them more adapted to the challenges of the transition. France has a lot of adapting to do to achieve the zero-carbon objective by 2050, but the solutions exist and this energy transition is entirely possible from the point of view of the electricity sector.

Key Words:

Energy Transition, French Electricity Sector, Renewable, Grid, European Electricity Markets

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1. Introduction

The image of the French electricity sector and EDF (Electricité de France), its main player, are difficult to dissociate from nuclear power. Indeed, the 1970s marked a transition to "all nuclear" (net zero). Even today, France is heavily dependent on its reactors. However, today's world is nothing like that of the 70s. Over the past 50 years, numerous events have changed how we think about energy production in France and Europe. These include the numerous oil crises, the nuclear disasters of Chernobyl and Fukushima, the liberalization of the European market in the 2000s, the economic crisis of 2008, which led to 2009 being the first year since 1945 with a reduction in global electricity consumption, the COVID-19 crisis and the subsequent contraction of the world economy, and more recently the war in Ukraine, which cut Europe off from Russia, their leading supplier of gas and oil (LEBROUHI et al., 2022).

Above all, over the last 20 years, the world has realized that greenhouse gas emissions caused by fossil fuel use have disastrous global warming effects on all ecosystems. It threatens our way of life and the very equilibrium of our societies. The World Climate Conference COP 26 in 2022 called for urgent action by all countries to limit global warming to less than 1.5°C above pre-industrial levels (LEBROUHI et al., 2022). Like every other country in the world, France must therefore embark on an ecological transition. The main objective put forward by the European Union and the French government is to achieve net-zero emissions by 2050. In other words, France must have a zero CO_2 emission/absorption balance on its territory by 2050, which must be an absolute political priority.

We are specifically talking about energy transition for the sector we are interested in. The word "transition" indicates that profound changes will be necessary, that we will change our paradigm, and that our way of producing and consuming energy will change. What is certain is that the electricity sector is a significant element in this transition. To meet environmental challenges and limit our CO_2 emissions, we must commit to developing one form of energy in particular: decarbonized electricity (LEBROUHI et al., 2022).

When we speak of decarbonized electricity, we often think of intermittent renewable energies such as solar and wind power, but nuclear power also produces decarbonized electricity (MILLOT et al., 2020). However, using nuclear energy entails risks and produces radioactive waste over the long term, so it is also a question for society to think about the future of this energy. A country can choose to stop using it, as is the case in Sweden and Germany, or to continue using it (MILLOT et al., 2020). In any case, we need to consider replacing nuclear power with renewable energy (BONIN et al., 2019). We also need to think of developing storage capacities to compensate for the intermittency of these energies (PERCEBOIS et al., 2019).

The objective of this work is to examine how the French electricity system is constructed today, how this sector will achieve its energy transition by 2050, and what the challenges that go hand in hand with this transition are.

To this end, this work is divided into four distinct chapters. The first part is this introduction, the second presents the French electricity sector, analyzing the grid and the electricity market, the third looks at France's approach to the energy transition, looking at the different future scenarios and the challenges that the grid and markets will have to meet, and the fourth part concludes this work.

This project began with a simple desire to explain the energy transition and its impact on the French electricity system. It became clear quite early on that to fully understand the issues at stake, it was essential to understand the various aspects of the French electricity system. So, in the course of this work, my objective become to give an overview of the various aspects of the system.

Of all the sources used in this work, it's in particular the various RTE reports that have guided my reflections on the future of the French system, the article by LEBROUHI et al (2022) that has given me a clearer vision of the issues involved in the energy transition in general, the reports by the court of audit (CC) that explain the costs of electricity and how the markets work, and the reports by the CRE that detail each electricity market.

2. The French electrical sector today

The French electricity matrix in terms of production seen in Figure 1 is mainly nuclear (RTE, 2022-1). However, it has a quarter share of renewable energy, half of which comes from hydroelectric power plants (with reserve dams or run-of-river) and the other half from wind, solar, and thermal renewable sources (Table 1). This primarily nuclear production comes from past political decisions and substantially impacts the structure of the French system and the development of renewables. Nuclear power also makes France a country with low-carbon electricity production.

	Installed Capacity (GW)			Part of the capacity			Production (TWh)			Part of the production		
	2020	2021	2022	2020	2021	2022	2020	2021	2022	2020	2021	2022
Nuclear	61,4	61,4	61,4	45,1%	44,1%	42,6%	335,4	360,7	279,0	45,1%	69,0%	62,7%
Hydropower	25,7	25,7	25,9	18,9%	18,5%	18,0%	65,1	62,5	49,6	18,9%	12,0%	11,14%
Fossil	18,9	17,9	17,7	13,9%	12,9%	12,3%	37,6	38,6	49,2	13,9%	7,4%	11,05%
Including Gas	*12,5*	*12,8*	*12,8*	*9,2%*	*9,2%*	*8,9%*	*34,5*	*32,9*	*44,1*	*9,2%*	*6,3%*	*9,91%*
Including Fuel	*3,4*	*3,3*	*3,1*	*2,5%*	*2,4%*	*2,1%*	*1,7*	*3,8*	*2,2*	*2,5%*	*0,7%*	*0,49%*
Including Coal	*3*	*1,8*	*1,8*	*2,2%*	*1,3%*	*1,2%*	*1,4*	*1,9*	*2,9*	*2,2%*	*0,4%*	*0,65%*
Wind	17,6	18,8	21,2	12,9%	13,5%	14,7%	39,7	36,8	38,1	12,9%	7,0%	8,56%
Solar	10,4	13,1	15,7	7,6%	9,4%	10,9%	12,6	14,3	18,6	7,6%	2,7%	4,18%
Renewable Thermic and waste	2,2	2,2	2,3	1,6%	1,6%	1,6%	9,6	10	10,6	1,6%	1,9%	2,38%
Total	**136,2**	**139,1**	**144,2**	**100,0%**	**100,0%**	**100,0%**	**500,0**	**522,9**	**445,1**	**100,0%**	**100,0%**	**100,0%**

Table 1: French electricity Capacity and Production from 2020 to 2022

Sources: RTE (2022-1) and RTE (2021)

2.1 Brief history of EDF and its nuclear power plants

2.1.1 From 1946 to 1991

The French power plants are all owned by the company Electricité De France, known as EDF (EDF, 2022), which makes it a major player in the French electricity system. EDF was created in 1946 at the same time as Gaz De France (GDF). These two companies were created as state companies by the takeover and merger of all the existing players in the sector. There was then a state monopoly for producing, transporting, distributing, and selling electricity and gas for all French households and companies connected to the network. From 1948 to 1952, the Marshall Plan provided 36% of EDF's investment expenses, which allowed the French government to invest in significant projects. In particular, large hydroelectric dams were built during this period, as well as numerous thermal power plants (EDF 2022).

After the first oil crisis in 1973, France, which had no oil resources, decided to turn its energy production towards nuclear power (MILLOT et al., 2020). This decision is also linked to France already having important research utilities in the nuclear field due to its nuclear bomb project developed after world war 2. The first French nuclear bomb was tested in 1960. On the 6th of March, 1974, the Messmer plan was announced. It provided for the launch by EDF of the construction of the thirteen first French nuclear power plants with a capacity of approximately 900 MW (VP, 2023). The company chosen to construct all the French nuclear power plants is Framatome. Framatome (Franco-American Atomic Construction Company) was created in 1958 by several French and American companies, including Westinghouse, which then had a license in pressurized water reactors (PWR) (VP, 2023). Therefore, all the reactors currently in service in France are so-called Generation II PWRs. Between 1972 and 2002 (the last project was initiated in 1991), EDF built and commissioned 58 pressurized water reactors on 19 sites in France, all with a net power of between 890 and 1500 MW (IRSN, 2023). French reactors are fairly well distributed across the country (Figure 3). All the reactors are located along a major river or the sea, because the power station needs water to operate, produce energy and cool the reactors (IRSN, 2023). Of these 58 reactors, only two were shut down in 2020.

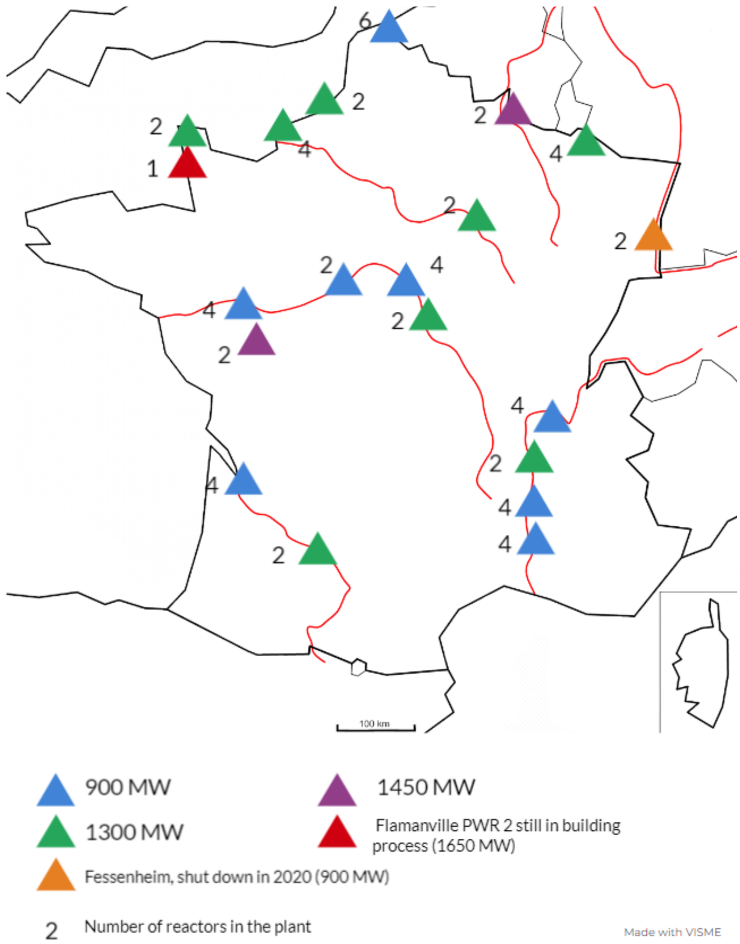

Figure 1: Localization of the French nuclear plants

Source: By the author based on data from IRSN (2023)

2.1.2 From 1991 to 2020

During this period, the construction of power plants slowed down. This is due to several factors, which may be an already efficient fleet meeting the national demand, but also a less favorable public opinion than before. The population started seeing the risk of nuclear plants after the Chernobyl disaster in 1986 (VP, 2023). After the disaster, a radioactive cloud crossed Europe, and the French authorities said at this time that the cloud did not cross the French border. The hypocrisy of the French government during this incident did not help either. After the Fukushima nuclear disaster in 2011, Germany chose to phase out nuclear generation, which impacted political decisions at the European and national levels (LEBROUHI, SCHALL, 2022). In 2015, President François Hollande announced that France would only produce 50% of its energy with nuclear power by 2035. In addition, the only nuclear reactor project launched in France during this period has many problems and is greatly delayed. It is a “European Pressurised Reactor” (EPR) called 3rd generation reactor (IRSN, 2022), started in 2007 and still not finished. The construction of this plant costs much more than expected, which cause problems with public opinion (CC, 2021).

From the year 2000, EDF lost its monopoly on the production and sale of electricity following the opening of the market. Indeed, in 1996 directive 96/92/CE of the European Commission imposed the opening of the electricity production market to competition and the end of the national monopoly on the supply of electricity. Since 1999, sites consuming more than 100 GWh/year can choose their electricity supplier (ECO, 2022). In 2007, all customers, companies, or households can choose their electricity supplier. In 2004, EDF became a public limited company listed on the stock exchange, but the State must retain at least 70% of its capital. This partial privatization further limits EDF's ability to invest in major projects during this period (EDF, 2023).

In 2020, the Fessenheim power plant was definitively shut down, and dismantling began. It is the first PWR to be dismantled in France, which poses new problems in storing radioactive waste and cleaning the site (IRSN, 2023).

2.1.3 From 2020 to Present

Other power plants had planned their shutdowns in the next few years, but in February 2022, President Emmanuel Macron announced the extension of the operation of all reactors that have the technical possibility (ECO, 2022). In the same announcement, he asked EDF to launch the construction of 6 third-generation nuclear power plants and the possibility of building eight more by 2050. These plants will be of the "European Pressurised Reactor 2" (EPR 2) type. The EPR 2 draws on the lessons learned from the EPR 1 (IRSN, 2022), which has been in the planning stages since 2007 and has experienced numerous delays, and should be completed in 2024. The building process has been simplified, and the technology improved. Nevertheless, the Institute for Radiation Protection and Nuclear Safety (*Institut de Radioprotection et de Sureté Nucléaire* – IRSN) has not authorized EDF to increase the power of the new reactor, which will remain between 1500 and 1600 MWh. In anticipation of these large projects, the France parliament voted in 2018 on the renationalization of EDF, which should be completed on the 8th of June 2023, and EDF has bought 70% of the company Framatome. This nationalization will facilitate the construction of future power plants. And increase the French government's share of decision-making and investment in construction projects. It is important to remember that energy production is a significant issue of national sovereignty, and the recent crises of COVID-19 and the war in Ukraine have shown that global supply chains can cease functioning because of natural or geopolitical hazards. France's current challenge is to provide the country with production capacities that do not depend on these international supply chains or depend on them as little as possible—at the same time, moving forward on the path of the energy transition.

2.1.4 Fuel supply

Nevertheless, the national sovereignty issue raises the question of uranium supply in France. For this purpose, the Euratom (European Atomic Energy Community) Supply Agency (ESA) publishes quarterly and annual reports on the nuclear fuel supply capacities of the members. If we look at natural uranium, the main component of nuclear fuel, 96% of the 11,975 tons delivered to the European Union came from five leading producers: Niger, Kazakhstan, Russia, Australia, and Canada (Figure 4) (ESA, 2021). The supply is not so diversified, which may prove to be a problem in the future. Nevertheless, the European Union had, in 2021, three years of nuclear fuel storage. These figures are at the European level, but France is the most dependent on these nuclear fuel supplies, as it has 56 of the 106 nuclear reactors in operation among Euratom members. France uses about 8,000 tons per year of natural uranium, which is around ⅔ of the amount imported into Europe every year (ECO, 2022).

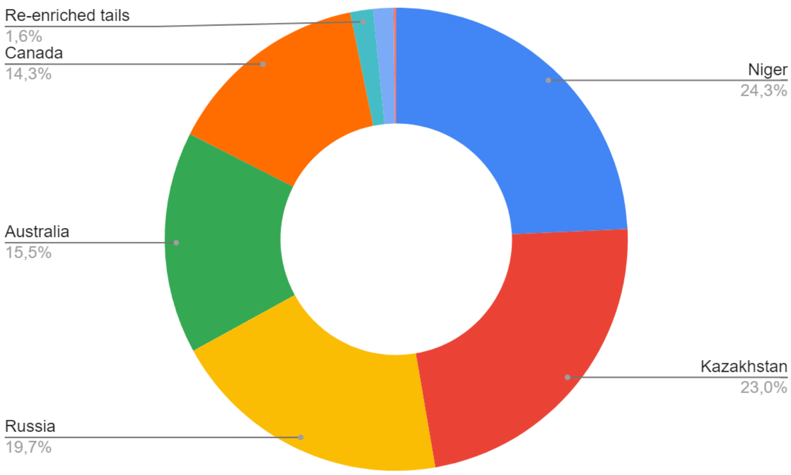

Figure 2: Origin of the natural uranium in Europe

Source: Based on data from ESA (2021)

However, even though natural uranium reserves are located outside of Europe, 31% is extracted and transported by the French company Orano (formerly Areva), notably thanks to its mines in Niger and Kazakhstan. The imported natural uranium is then enriched in order to produce nuclear fuel. This enrichment is done at 62% in Europe, mainly by Orano (ESA, 2021).

2.1.5 Nuclear waste management

The treatment of nuclear waste is also an important issue. The French policy on waste treatment is explained in the National Plan for the Management of Radioactive Materials and Waste, published every three years; the fifth was published in 2021 (IRSN, 2022). The publication of this national plan is debated in the Senate, which shows the importance of this subject for society.

First, some of the fuel used in nuclear reactors is recycled into a fuel known as MOX (for Mixture of Plutonium Oxide and Uranium Oxide). More precisely, the "isotope uranium 235" is used in fission reactions. After irradiation, the used fuel contains 1% plutonium and still 1% "uranium 235". The plutonium produced during the reaction and the uranium still present in the spent fuel are sent to an AREVA processing center for re-enrichment. The use of MOX fuel began in France in 1987, and 22 of the 56 reactors are authorized to use this fuel. Approximately 120 tons of MOX fuel is used in French power plants each year, and IRSN estimates that this represents a saving of 900 tons of natural uranium or more than 10% of total consumption. Unfortunately, spent MOX fuel cannot yet be recycled, which is one of the future research objectives.

Waste that cannot be recycled, from dismantled centers, objects used near sources of radioactivity, or from the processing of spent fuel must be managed. Wastes are classified by the activity level of the radionuclides (low, medium, high) and by the lifetime of the radionuclides (short-lived for a radioactive period of less than 31 years and long-lived otherwise). Short-lived or low-level long-lived wastes are stored on the production site or in specialized storage centers managed by the national agency to treat radioactive waste (*Agence Nationale pour la gestion des Déchets Radioactifs* – ANDRA). The real problem comes from managing long-lived medium and high-level wastes, which concern only a small quantity of waste, estimated at 10,000m3 by the end of the use of nuclear power plants. Currently, ANDRA is developing the Cigéo project, which aims to store these wastes at a depth of about 500 meters in a clay formation (ANDRA, 2022). However, this raises many questions, including how to inform future generations that dangerous wastes are stored there. Currently, these wastes are temporarily stored on their production sites while waiting for a long-term solution.

2.2 Other players in the French electricity system

2.2.1 Engie and the others

As we have seen in the electricity matrix, production is not only nuclear. Moreover, electricity production is liberalized, and one of the objectives of the competition between electricity suppliers was to allow them to invest in electricity production and become producers and suppliers. However, few players have invested in production. Nevertheless, Engie (formerly GDF) has about 10 GW of production capacity (around 8% of the total), mainly from gas-fired power plants, but also from hydroelectric power, solar power (thanks to the acquisition of Solairedirect in 2015), and wind power. On a global scale, the group has 100 GW of generation capacity, of which 34,4 are renewable (ENGIE 2022). Engie and EDF produce about 95% of the electricity in France (EDF, 2022). The remaining 5% is divided between smaller renewable producers. Like Neoen for solar, Unite for hydraulic, and Boralex for wind. The production of energy in France is thus a quasi-monopoly of EDF and Engie but with an arrival of new actors on the renewable market. Producers can integrate the market, but the French government plans the construction of power plants and subsidizes the production of renewable electricity through different mechanisms.

2.2.2 RTE

The transmission and maintenance of the network on high voltage lines are provided by *le Réseau de Transport d'Electricité* (RTE). RTE is an independent company but 100% owned by EDF. Transport has not been privatized because it is a natural monopoly, there is only one network and it would not be efficient to put it in competition (FINON, 2019). RTE publishes real-time data on European production and consumption; its objective is to manage production and delivery to the customer after the SPOT price has been determined in the day-ahead market. The transmission is done nationally but also internationally with import and export with the European neighbors.

The French electrical network has 106,000 km of very high voltage (440,000 V and 225,000 V) and high voltage (90,000 V and 63,000 V) lines that connect production plants with urban areas and large industrial customers (RTE, 2022). Production, especially nuclear energy, is relatively well distributed over the territory. The network is complete and serves all the urban areas, which means that the network has good resilience.

2.2.3 European exchange

For electricity trade on a European scale, RTE has 46 cross-border lines connected to Italy, Spain, Germany, Belgium, Switzerland, and the United Kingdom. It should be noted that 2022 was an exceptional year because France had to import electricity, whereas, since 1980, France has been a net exporter. As we can see in Figure 4, France had to import 16.5 TWh or 4% of its electricity from Germany, Belgium, the United Kingdom, and Spain (RTE, 2022-1). At the same time, it remained a net exporter to Italy and Switzerland. In comparison, in 2020 and 2021, we observed two years with a net export of more than 43 TWh (RTE, 2021).

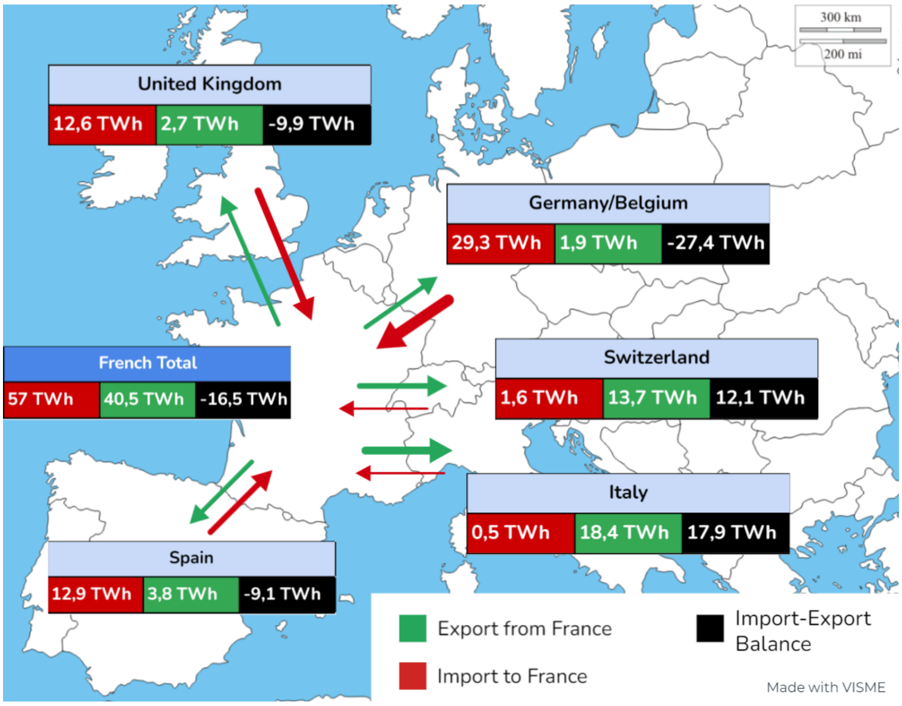

Figure 3: Electricity commercial exchange between France and other countries in 2022
Source: By the author based on data from RTE (2022-2)

The year 2022 was exceptional because the level of the dams was historically low during the summer, which limited their use. Furthermore, half of the nuclear plants were under maintenance during the summer of 2022 for two reasons (RTE, 2022)—first, a delay in the multi-year maintenance schedule due to COVID-19. Second, a corrosion problem was identified in one plant, which led to the control of all the reactors.

This 2022 situation shows us two things about the French electrical system. Firstly, the dependence on nuclear power plants, all of the similar technology and built over a short period, can be a problem. Because a defect that occurs in one plant is likely to occur in another, and this will become an increasing problem as the nuclear fleet ages. The second remark is that the interconnection of the French network with the European network has avoided any problem of lack of electricity. These two points are essential to understand the political decisions concerning the future of the French electricity sector.

Indeed, the European electrical network's interconnectivity is a significant energy transition challenge. With the development of renewable energies, which are not dispatchable generation sources, the network needs to find flexibility elsewhere. Interconnection is a way to make the European system more adaptable and to allow it to meet demand better, using the complementarity of sources located at long distances

(LEBROUHI, SCHALL,2022). And therefore, do not have the same weather conditions at a given time and therefore not the same output in terms of renewable energy. Today, France has a capacity of 15 GW of interconnected lines with its neighbors, and the ten-year network development plan (*schéma décennal de développement du réseau* SDDR) provides for a doubling of capacity by 2035 (SDDR, 2021).

2.2.4 Enedis

The distribution and connection of the users to the network are made to 95% by Endis, also owned by EDF (ECO, 2022). The distribution is also a natural monopoly; nevertheless, we find some cities like Grenoble or Strasbourg where regional companies owned directly by EDF make the distribution. The French network, composed of RTE and Enedis, connects 32.8 million residences, representing a consumption of approximately 152 TWh in 2019, and 5,1 million non-residential sites representing a consumption of approximately 280 TWh in 2019.

2.3 Electricity Markets

There are several electricity markets in France: the retail market, where consumers buy their electricity from competing suppliers, and the wholesale markets, which consist of the various means of interaction between producers and suppliers. These markets interact with the other players in the system in different ways, which are shown in the Figure 5 and which we will explain in more detail.

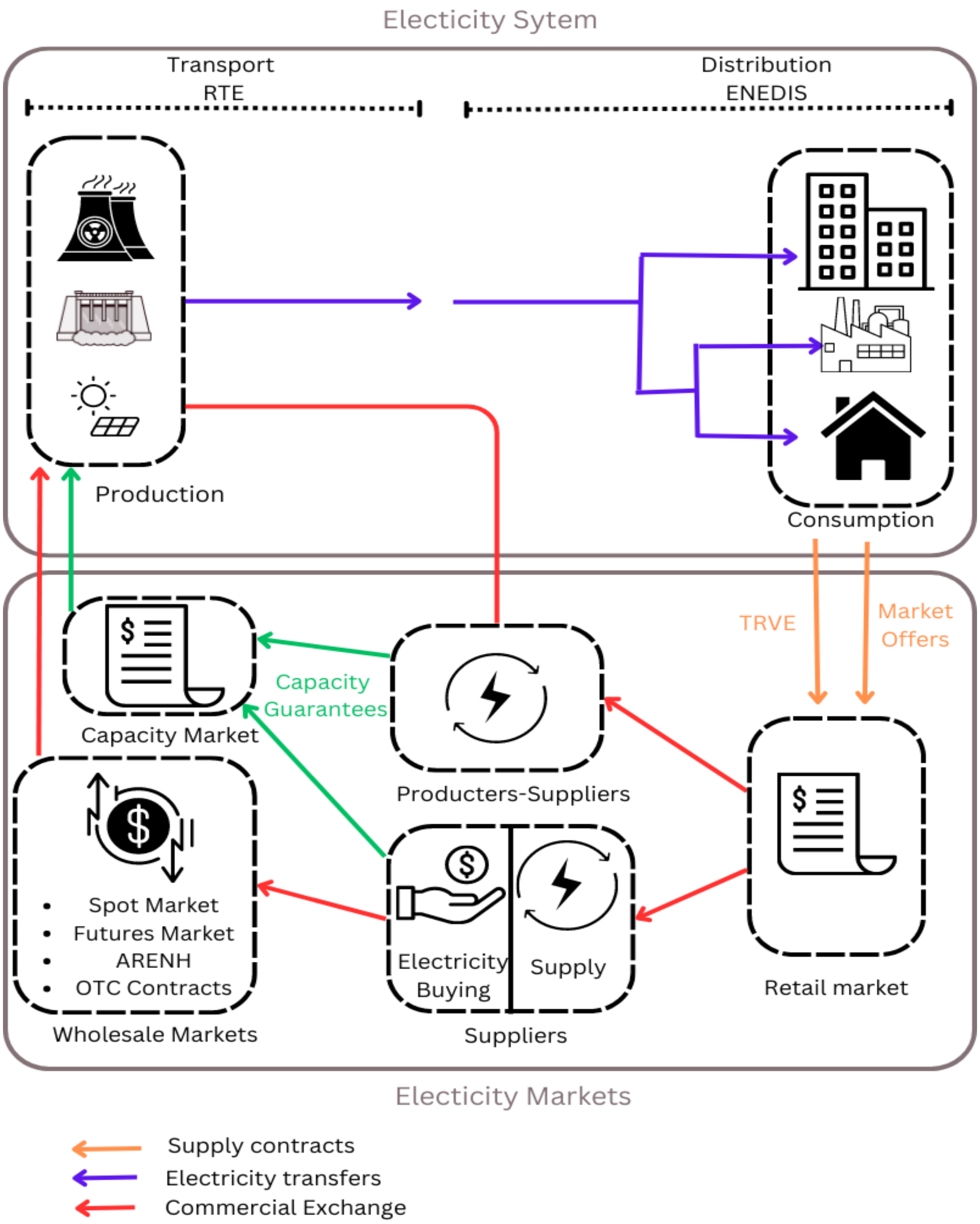

Figure 4: Interaction between the electricity system and markets

Source: Author

2.3.1 The retail market

The retail market has been open to competition since 2007; any consumer can buy electricity from the supplier he wants. Therefore, more than 80 suppliers in France trade electricity (ECO, 2022). Their work consists of customer service, billing, and evaluating their customers' needs. Evaluating is essential because each supplier has to buy the right to draw electricity from producers on the wholesale market beforehand. EDF is the largest electricity supplier, with about 55% of the market share in the fourth quarter of 2022, according to the retail market observatory of the energy regulation commission (*Commission de régulation de l'énergie* – CRE). However, EDF has the special status of "historical supplier" as opposed to the "alternative suppliers", which do not produce electricity. This status obligates it to propose a market offer and an offer at the regulated rate of sale of electricity (*tarif régulé de l'électricité* TRVE). The CRE determines the TRVE once a year. It is an estimate of the cost of purchasing electricity by alternative suppliers.

Therefore, the competition in the retail market is mainly between alternative and historical suppliers. The suppliers on the retail market aim to set a price below the TRVE when the price of energy is stable or falling, which allows them to gain customers and thus make a profit. Nevertheless, we observed that in 2022 prices have risen to a historic high, and suppliers raised their prices to lose customers (CC, 2022-1). This customer loss allowed them to resell the surplus electricity already purchased at the high market price, while they had been able to buy electricity drawing before the price increase. The electricity price crisis that started in 2022 and is still ongoing in 2023 allows the alternative supplier to make large profits. The crisis of 2022 shows the limits of the retail electricity market and the limits of the TRVE determined only once a year. The trading of electricity allows the alternative supplier to make profits at the expense of EDF.

2.3.2 The wholesale markets

This subsection will describe the four instances of the wholesale market, the ARENH, the OTC contracts, the futures market, and the SPOT market (CC, 2022-1).

The first way for suppliers to buy electricity drawing rights is the Regulated Access to Historical Nuclear Electricity (ARENH). Since 2011, the State has obliged EDF to make 100 TWh of nuclear-generated electricity available at a price of 42€/MWh. And this regardless of the market price of electricity. Suppliers must apply for access to the ARENH once a year, and the CRE will allocate a certain number of TWh. Let's consider that alternative suppliers have 45% of the electricity supply and that we can approximate the consumption in 2022 at 450 TWh. ARENH represents about 50% of the ~200 TWh needed by alternative suppliers. The idea behind this mechanism is to allow EDF's competitor to benefit from the low costs of nuclear technology, whose infrastructure costs have been largely amortized over the past 40 years. Nuclear fuel is also relatively low-cost compared to other fuels (CC, 2022-1).

The second component of the wholesale market is the OTC contracts. These are contracts made directly between suppliers and producers. They are made between one week and three years in advance and therefore do not go through the market. For example, as a supplier, EDF makes OTC contracts with EDF as a producer. The OTC contracts make the wholesale electricity market complicated to analyze because the producers and suppliers do not reveal their OTC contracts publicly.

The first major exchange in the wholesale markets is the futures market. Suppliers buy electricity drawing rights between one week and three years in advance. The price of electricity in the futures market is unique and is the average of the expected SPOT prices for a given period. It makes it difficult to estimate the actual price at the time t that a supplier has paid for electricity because the supplier may have purchased electricity at any time. Suppliers aim to maximize their profit while securing the necessary quantity for their customers by purchasing electricity drawing rights at the right time.

The second electricity exchange is the SPOT market or Day-ahead market. It is a European market for which there are two different exchanges, EPEX and Nord Pool which use a shared algorithm called "Euphemia" (EPEX, 2022). It is a balancing market where suppliers and producers buy and sell according to their needs one day before the electricity is put on the grid. The market is volatile, with the price varying hour by hour over the next day, depending on the expected demand. This market will calculate the price of electricity and the flows on the interconnections between system members in a unified way on a European scale. In this market, the SPOT price equals the variable cost of the most expensive plant that will be operated.

2.3.3 The spot market and merit order

The wholesale market, therefore, provides the accounting connection between suppliers and producers. It has a production organization function. Indeed, the day-ahead market will determine the SPOT price and thus make it possible to determine which power plants will operate the next day. The production schedule of the power plants can only be determined once the SPOT market has operated (CRE, 2022).

Each European productor sends an order list to the SPOT market that says which of their plants can produce a certain amount of energy at an x price. Each "alternative supplier" will send an order list with the amount of power it needs to buy to supplement what it has already bought on other markets. With this, the market will use the Euphemia algorithm to determine a single European price and then, according to the technical constraints of energy transport, a price for each country based on this European price (EPEX, 2022).

This price is based on the "merit order", the activation of the power plants from the lowest variable cost to the highest variable cost. Solar, wind, and run-of-river hydro are always called first because they have no fuel and, therefore, only fixed costs (CC, 2021). Then there is nuclear power, which also has a low variable cost with a fuel costing between 3 and 10€/MWh, depending on the estimates. Then finally, the dispatchable sources of 2 different types:

- The hydroelectric power plants with dams for which the variable price corresponds to an estimate of the impact of the use of water on the other activities depending on the dam (irrigation, the water supply of the agglomerations, leisure, environment, and others).
- Fossil fuel thermal power plants. Gas-fired power plants are called first because thermal power plants emit CO_2 and have to pay a tax that depends on their emissions in tons of CO_2. Gas-fired power plants emit less than oil and coal-fired ones, so their variable cost is lower.

Once the price has been determined, RTE, which also knows the power plants' production capacities and the network's technical constraints, will create the final production program. And ensure the balance between supply and demand during the day (RTE, 2022).

The production program is therefore based on the selling prices offered by the producers. A central agency does not determine it like in other countries (ONS in Brazil, for example). The SPOT market does not have visibility on the actual conditions of use of the power plants, which can lead to a lesser performance than centralized planning.

However, the advantage of this system is the interaction between all the European markets. If there is a technical possibility, a country will use a foreign power plant at a lower cost than the ones in its territory. This market characteristic will become increasingly important in the future with the increase in interactions between countries.

2.3.4 The constitutive problems of the market

However, the wholesale market is not fully functional; it has yet to succeed in meeting its objective, which is to encourage private investment in electricity production facilities. Indeed, the volatility of market prices does not allow private investors to be sure of the profitability of the investment in a power plant. Worse than that, the market causes a risk of closing down unprofitable power plants that are only used during peak consumption. For this, two mechanisms had to be put in place.

The first is the capacity market set up in 2017 to encourage used dispatchable generation plants to remain in operation, mostly gas-fired power plants (RTE, 2021). In this market, the operators of production capacity or demand reduction capacity (industrial companies that can stop their consumption during certain hours) sell capacity guarantees issued by RTE. These capacity guarantees ensure that they will be able to produce or not consume a certain number of MWh during a winter peak. Suppliers must buy these capacity guarantees to meet their customers' needs during these consumption peaks. These capacity guarantees make it possible to finance dispatchable sources and prevent demand from exceeding supply during the peaks (FINON, 2019).

The second is the long-term call for tender (*l'Appel d'Offres de Long Terme* AOLT) mechanism used for the first time in 2020 to stimulate the building of electricity storage facilities (RTE,2021). The aim is to facilitate new investments by providing visibility on a stable price. The State will ensure a stable electricity price for the plant's first seven years of operation.

Nevertheless, despite these two mechanisms, very few dispatchable plants are planned, forcing the State to subsidize construction well above the market price.

The wholesale electricity market does not stimulate investments in renewable energies either due to low costs and a lack of visibility. Indeed, the Levelized Cost of Energy (LCOE) of renewable energy production is estimated in the Court of Audit's system cost report (CC, 2021). It is estimated between 50€/MWh and 70€/MWh for onshore wind, between 98€/MWh and 117€/MWh for offshore wind. From 45€ for a solar power plant with a capacity between 10 and 30 GW located in the southern part of France and 81€ for a plant of less than 2,5 GW located in the north of France. However, before

2021 the wholesale price of electricity on the SPOT market was below this price (32,2 €/MWh on average for 2020). Therefore, the government created 2016 a tax called contribution to the electrical public service (*Contribution au Service Public de l'Electricité* CSPE) to assure renewable energy producers that their selling price will be above their fixed costs. This tax was 22.5€ for 2016/2021 but was almost abolished in 2022 due to the cost of electricity being above the cost of renewables (ECO, 2022).

The second major problem in the market is the correlation between gas and electricity prices. Indeed, the SPOT price of electricity increased significantly at the end of 2021 and has remained very high until today, with a peak in 2022 (CC, 2021). It is directly related to the price of gas, which has also increased due to the post-COVID-19 economic recovery and the war in Ukraine. The war caused European countries to stop buying gas from Russia, while it was their leading supplier, which increased the buying cost. As we saw before, the SPOT price is the price of the variable costs of the most expensive plant. However, France's most expensive power plant is almost always a gas power plant because it is the most used means of dispatchable electricity production. So even if gas-fired power plants only represent 6 to 10% of total electricity production, the price of electricity is entirely correlated to the price of gas.

Therefore, the European wholesale markets are a complex structure with many structural problems that require the State to intervene regularly to ensure its functioning. In its 2022 report, the French Court of Auditors states that "in the absence of public intervention, the opening to competition at the European level would have resulted in the supply of French customers at wholesale electricity prices that would have exceeded the production costs of the French fleet. The surge in wholesale electricity prices in 2022, in the wake of gas prices, illustrates this risk." The current electricity price crisis is not a crisis of production but a market crisis.

To conclude this section on the electricity markets, another direct quote from the report of the “Cour des Comptes” on the organization of the markets may be of interest: "The results of the public intervention are not satisfactorily controlled. This observation calls for clarifying and prioritizing the objectives pursued to determine the most appropriate methods for regulating the electricity markets."

The markets do not allow complete government control over the energy sector today but still need regular governmental intervention. Moreover, this will surely be a problem in future renewable energy development. The political will for a green transition must be aligned with markets and economic mechanisms that encourage it, not restrict it.

3. The electricity sector in the energy transition

For some years, one word has been uttered in every political debate: ecological transition. In 2017, the French Ministry of Ecology was renamed the "Ministry of Ecological Transition".

In France, energy transition means many things, but above all, the goal of net-zero emissions by 2050. It means that the economy will be entirely decarbonized. France's CO2 emissions will be entirely absorbed by the country's forests and other natural areas. It raises a number of issues, and in particular, for our purposes, a profound change in electricity production (MILLOT et al., 2020). Fossil-fired power stations will be shut down to meet these CO2 emission targets. Furthermore, France's nuclear power plants will be reaching the end of their useful lives. The debate on decarbonized electricity production will mainly focus on the balance between renewable energies and new nuclear reactors (RTE, 2022-2). Political decisions will have to be taken to ensure France's energy supply. It means a high penetration of intermittent renewable energies in the mix and a grid reform to meet future technical challenges.

3.1 Renewable sources in France

Today, France's electricity production is not very diversified. It, therefore, faces significant challenges in integrating renewable energies into its energy mix (MILLOT et al., 2020). Let us look at the current status and development targets for the three primary intermittent renewable sources.

3.1.1 Wind power

France began developing its onshore wind farm in the 2000s (RTE 2021). Capacity became substantial in 2006 when it passed the 1 GW mark. In the figure 6 we can see that the production has been steadily increasing until 2021, which was a historically low year in terms of wind generation, mainly due to poor wind conditions. In France, production capacity and wind potential are unevenly distributed (Figure 7). The Atlantic and Mediterranean coasts, as well as the north of France, are the best in terms of production.

The Hauts de France, Grand Est, and Occitanie regions account for 60% of production. Today, the installed capacity is 21,2 GW. The French wind farm is the 4th largest in Europe (3rd in the EU), behind Germany, Spain, and the UK.

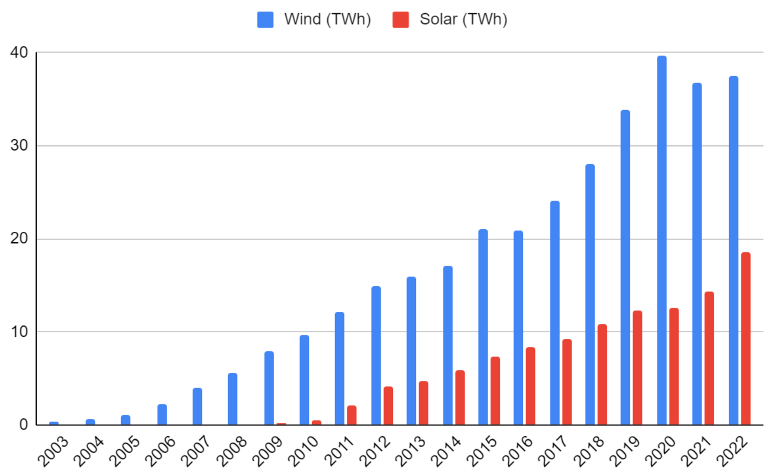

Figure 5: Evolution of the electricity production by wind and solar sources in France

Source: Based on data from PANO RTE (2022-1)

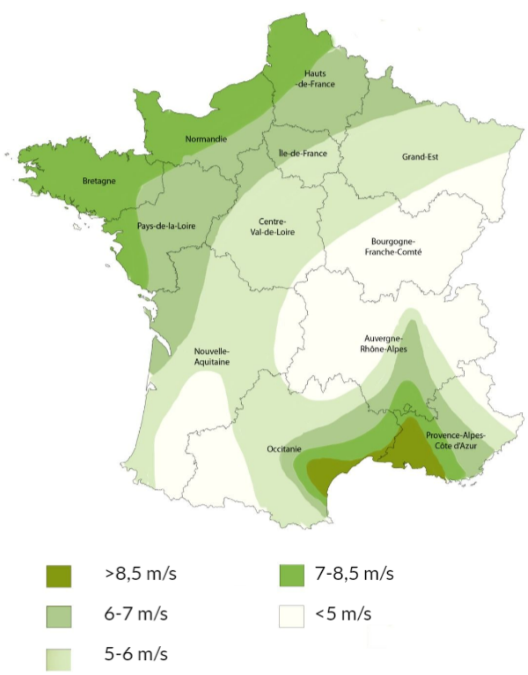

Figure 6: Wind potential map

Source: By the author based on data from ADEME (2023)

The first offshore wind farm, located off Saint Nazaire, was connected to the grid in November 2022. It has a capacity of 480 MW. 6 offshore wind farms are currently under construction, with a total capacity of 3 GW, including two scheduled for commissioning in 2023. Furthermore, six other projects are in the tendering phase. France aims to develop around 50 wind farms by 2050, with an estimated capacity of 40 GW (RTE 2021). The large-scale wind farms under development are all fixed-foundation, but three small pilot floating wind farms are also under construction, with a total capacity of 84 MW. This technology is not yet fully developed and needs to be improved before it can be marketed on a large scale, but the cost of this technology could turn out to be lower than that of seabed fixed wind turbines in the next few years (RTE, 2022-2).

Until now, the development of offshore wind farms has been limited by much higher costs than onshore wind turbines. Indeed, in 2020, the French National Audit Office estimated the LCOE of wind power at between €50 and €70/MWh for onshore wind power and between €98 and €117/MWh for offshore wind power (CC, 2021). These high costs need to be supported by subsidies to encourage the development of large-scale projects. Ademe estimates that wind power costs will fall by 40% for onshore wind power and 60% for offshore wind power by 2050 (CC 2021).

3.1.2 Solar energy

The development of solar power also began in France in the 2000s. However, the connection to the grid only began to appear in 2006, with an installed capacity of 4 MW, while 0.2 TWh was generated over the year. Growth has been continuous over the period from 2009 to 2022. By 2022, the installed capacity was 15.7 GW, and the annual production was 18.6 TWh. The capacity factor for French solar power is between 14 and 15% over the period 2014 to 2022. The year 2022 was also a record year in terms of installations on a European scale, with the installed capacity growing by 25% in one year. Europe's largest installed capacity is in Germany, followed by Italy, Spain, and France (RTE 2022-1).

French targets set by the Multiannual Energy Plan (*plan pluriannuel de l'énergie* PPE) are 20.1 GW of installed capacity by the end of 2023 and 35.1 to 44.0 GW by 2028. It is pretty likely that the 2023 target will not be met, as it would require the installation of 4.4 GW in 2023, which would be a historic increase in the installed capacity.

As we can see in the figure 8 production is highly seasonal . This high level of seasonality will pose problems for energy storage as capacity is developed. Fortunately, wind power complements solar power, producing more in autumn and winter (October to March), while solar power produces more in spring/summer (April to September).

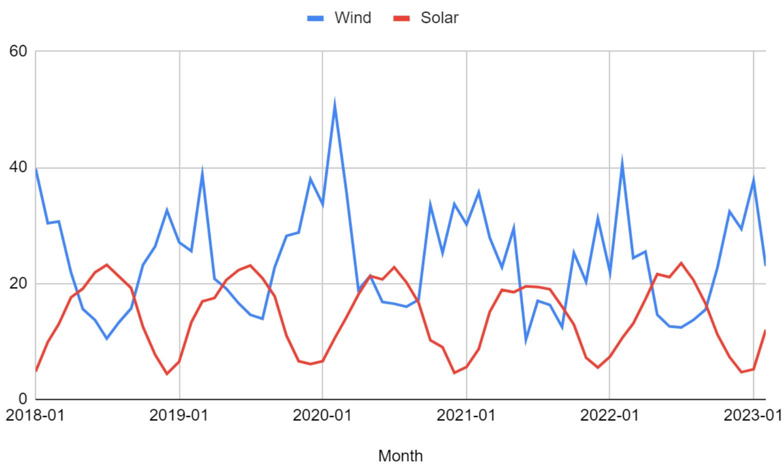

Figure 7: Average monthly charge factor for wind and solar production in France (%)
Source: Based on data from ORDRE (2023)

Like wind power, solar energy is highly disparate across France. Regarding solar potential, production capacity is higher in the south of France than in the north as seen in Figure 9. It is mainly due to a drier climate and, therefore, more sunshine (CC, 2021). This disparity explains the different costs of solar installations in different parts of France. These costs also differ between small and large-scale installations, as the scale factor significantly impacts solar installation (CC, 2021). In particular, the LCOE cost of residential solar systems with a surface area inferior to 30m2 (3 to 9 kW systems) is much higher than that of larger systems. Between 88€/MWh and 135€/MWh for 9 kWh installations and between 130€/kWh and 223€/kWh for installations of just 3 kWh (CC 2021). In comparison, the LCOE of a large solar plant (between 1 and 3 GW) can be only 45€/MWh (Table 2). However, the purchase price of solar panels is set to fall significantly over the next few years due to different improvements in the supply chain, such as technical progress in the factoring, the development of local French production, improved components recycling, and increased global production. ADEME estimates that the cost of solar panels will fall by between 50 and 60% between 2020 and 2050 (CC 2021). This fall would make small-scale installations more profitable.

	North	South
Solar central		
2 500 MW	81 €/MWh	56 €/MWh
10 000 MW	76 €/MWh	52 €/MWh
30 000 MW	65 €/MWh	45 €/MWh
Large size roof		
500 MW	97 €/MWh	67 €/MWh
2 500 MW	89 €/MWh	61 €/MWh
Medium size roof		
100 MW	91 €/MWh	63 €/MWh

Table 2: LCOE 2019 for solar installation

Source: CC (2021)

Given the disparity of solar radiation across the country seen in Figure 9, it seems logical that installed capacity is unevenly distributed. In 2020, 60% of installed capacity was situated in the southern regions of France: Nouvelle-Aquitaine (25%), Occitanie (20%), Provence-Alpes-Côtes d'Azur (13%) and Auvergne-Rhône-Alpes (11%).

Figure 8: Solar radiation potential map

Source: Solargis (2019)

To meet the targets set by the PPE, the French government wants to encourage large-scale solar park projects with public subsidies such as the AOLT. The State also wants to decentralize production by encouraging individuals and businesses to build solar panels on their roofs. In 2021, the French Climate and Resilience Act will require all new buildings with a floor area of over 500m2 to have at least 30% of their surface covered by solar panels (ECO, 2022).

3.1.3 Hydropower

Today, hydroelectric power plants are the leading source of renewable electricity, with a total capacity of 25.9 GW and a production of 50 TWh in 2022. The French network includes 2,500 installations of 4 different types (HYDRO, 2023):

- Run-of-river power plants are unrestrained plants with a waterfall of less than 30 m. There are 2,300 of these in France, but they account for only 26% of capacity. They are of two kinds: run-of-river power plants on large rivers and small hydroelectric power plants, which are less than 10 MW installations. In these plants, electricity is produced in real-time, with no control over output. Production can vary according to river flow (EDF, 2023).
- Lock-type power plants are found in mid-mountain and low-relief regions, with a waterfall between 30 and 300m. These power plants have a small reservoir. They account for 16% of capacity, but only a small share of production, as the water in these plants, is often used for activities other than power generation (PANO, 2021).
- Lake power plants are found in high mountain areas, mainly in the Alps and the Pyrenees. They are located on rivers with low flows and steep gradients and account for 40% of capacity. They have waterfalls over 300m. Large reservoirs give complete control over production (HYDRO, 2023).
- The last type of hydroelectric power plant is the pumped storage hydropower (*Station de Transfert d'Energie par Pompage* STEP). This system consists of 2 basins at different altitudes. When the STEP is in pumping mode, it recovers water from the downstream basin to fill the upstream basin. In turbining mode, the water flows from upstream to downstream, producing electricity in a turbine. France has 6 STEPs with a total capacity of 4.2 GW for pumping and 4.9 GW for turbining

(HYDRO, 2023). They can be closed-circuit or mixed with a natural water flow from outside. The aim is to reach 8 GW of capacity by 2050, for which it will be necessary to develop basins upstream of existing lake power plants (RTE, 2022-2). Because the upstream basin is smaller than the downstream one, adding a STEP to an already existing dam is easier. It is currently the most cost-efficient means of energy storage.

Except for STEPs, which could be added to existing power plants, there are no major hydropower plant development projects. Only 1 to 4,5 MW power plants are being developed, or existing plants are being upgraded. France has almost reached the limit of its river capacity. Nevertheless, existing facilities will continue to be used in the future.

Hydroelectric power, which depends partly on altitude and watercourses, is also very unevenly distributed (Figure 10), with 46% of installed capacity in the Auvergne-Rhône-Alpes region, where the major Alpine lake dams are located. And 21% in Occitanie, mainly in the Pyrenees (PANO, 2021).

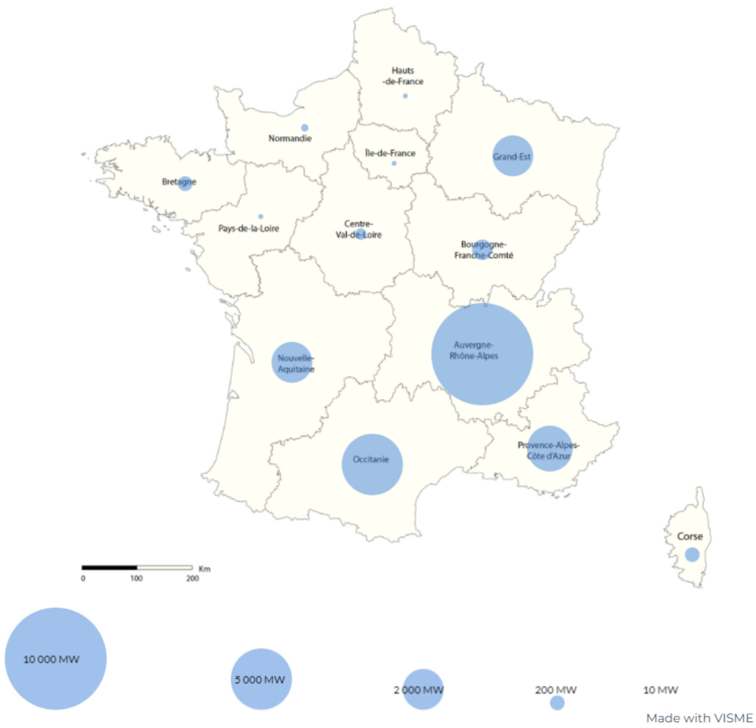

Figure 9: Hydropower capacity by region

Source: By the author based on data from PANO (2021)

3.2 The different scenarios and their hypothesis

Europe's Objective 55 is a law that aims to make carbon neutrality a legal obligation for all EU countries; this law is in the process of ratification. France has already written its 2050 carbon-neutral target in law (ECO, 2023). These national and European targets are political decisions that must be translated into action and public investment. These reforms and projects enable RTE to draw up scenarios for future electricity production and consumption (RTE, 2022-2).

3.2.1 Consumption scenarios

The energy transition, which aims to decarbonize energy production in France, requires increased electricity consumption. Indeed, in all the future scenarios proposed in different studies and in the RTE Energy pathways to 2050, the decarbonization of the economy involves the electrification of industry, transport, and heating. The scenarios assume a general reduction in energy use but an increase in the share of electricity in the energy mix. The RTE scenarios are based on the evolution of different variables:

- Sobriety: This variable evaluates societal changes that can be brought about. In sobriety scenarios, individuals reduce their travel as well as consumption of manufactured goods, use of heating in winter, and so on. The result is a sharp drop in energy demand.
- Electrification: In the most ambitious scenarios, transport is electrified, with electric cars and the arrival of electric heavy goods vehicles. Heating and industry are also electrified. In the low-electrification scenarios, some industrial sectors find it challenging to electrify and remain heavily dependent on fossil fuels, and policies to develop electric heating have not been successful.
- Energy efficiency: This mainly concerns the success of policies to renovate buildings. Better thermal insulation of buildings results in greater energy efficiency in terms of heating.
- Development of the hydrogen industry: This variable concerns the development of the energy storage industry through hydrogen production by water electrolysis.

The lowest scenario assumes an electricity consumption of 555 TWh, considering a high degree of sobriety and a change in social practices. The scenarios with the highest electricity consumption are those which assume the relocation of specific industries in France to reduce their carbon impact on the global economy, as well as the development of advanced industries. And the scenario which assumes very strong development of the hydrogen sector, with hydrogen replacing electrification in industry and transport. These scenarios assume an electricity consumption of around 750 TWh.

The selected scenario forecasts annual electricity consumption of 645 TWh in 2050, compared with 459.3 TWh in 2022. This scenario considers economic growth of 1,3% over the 30 years, no profound change in lifestyle, growth in the manufacturing industry to reach 10% of French GDP from industry, a successful thermal renovation policy, strong development of electric vehicles (95% of the cars in 2050), and massive development of the hydrogen sector to reach 50 TWh per year of electricity consumption by this sector.

As seen in the Figure 9 of consumption trends, the most significant difference between 2019 and 2050 will be the growing share of electricity in transport, the development of the hydrogen sector, and the reduction in the share of residential and tertiary consumption, mainly due to lower heating consumption.

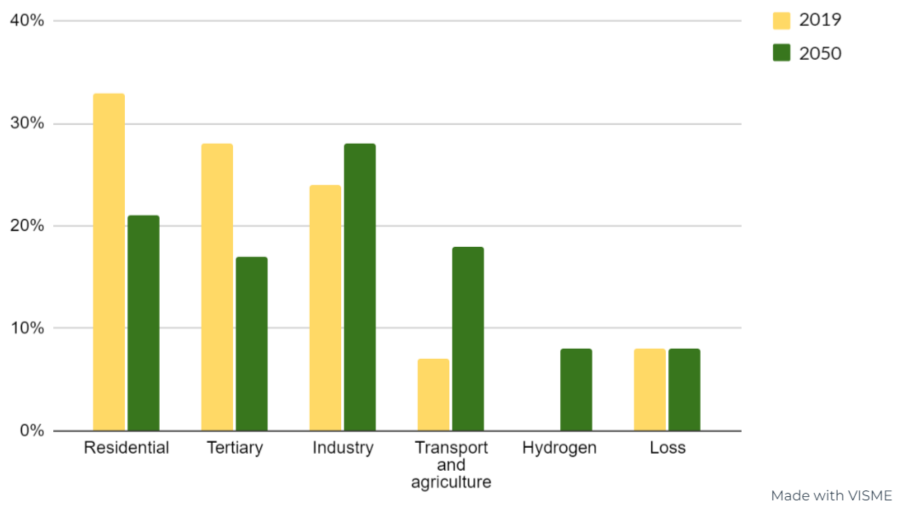

Figure 10: Structural evolution of the electricity consumption following the RTE 2050 selected scenario

Source: Based on data from RTE (2022-2)

3.2.2 Generation Scenarios

Generation, like consumption, has been put into scenarios based on different assumptions. Six scenarios have been created, three with new nuclear reactors planned and three without. It can be seen that, whatever the parameters adopted in all the alternatives, the installed capacity is much greater than that installed today (HONG et al, 2018). It is because the capacity factor of renewable energies is lower than that of nuclear or gas-fired power plants.

All scenarios share a number of parameters that remain stable (or almost so): hydropower (22 GW), bioenergy (2 GW), import capacity (39 GW), STEP (8 GW), vehicle-to-grid storage (1.7 GW), and demand flexibility capacity (between 13 and 17 GW, with 15 GW in 4 scenarios). A number of parameters that vary from scenario to scenario:

- The parameter with the most significant impact is nuclear capacity in the 2050 mix. In extreme scenarios, nuclear power is either not used at all, or historical nuclear power is used as long as possible (24 GW), and more than 14 new reactors are built (27 GW). In the four other scenarios, historical nuclear power retains a significant share (16 GW), and new nuclear power is between 0 and 23 GW.
- The variation in nuclear capacities also implies different capacities in terms of renewables, between 344 GW in the scenario without nuclear power and 135 GW in the scenario with the highest use of nuclear power. The most significant variation is for solar energy, which goes from development seven times the current level to 21 times the current level. Some scenarios assess the development of renewable energies, mainly through large-scale subsidized solar and wind power projects. In contrast, others focus on the situation where local players and energy communities are the leading players in the transition. In the case of large projects, wind power development is the most important, while in a decentralized production case, photovoltaics dominate the mix.
- The variation in decarbonated thermal power plants (methane, hydrogen) is also one of the parameters. It becomes the primary controllable source in scenarios without nuclear power, with 29 GW of capacity. In contrast, in the case of the most significant development of nuclear power, the development of renewable thermal energy is unnecessary.

- Battery storage capacity also ranges from 26 GW in the non-nuclear scenario to 1 GW in the nuclear scenario. Battery storage can be used to regulate differences in production and consumption. It assures flexibility over the grid in scenarios of extensive introduction of intermittent energy sources.

The articles studied show that 100% renewable scenarios are unrealistic from a technological and economic point of view. A 100% renewable energy mix "involves an unrealistic improvement of the interconnection, of the demand smoothing and of the storage capacity" (BONIN et al., 2019). The article by HONG et al. (2018) it is even said that, in the case of Sweden, the complete replacement of nuclear production by renewable energies would be neither economic nor ecological since, in their scenarios, the cessation of nuclear power would require the development of dispatchable gas-fired power plants to meet demand throughout the year, because of the intermittent nature of renewable sources.

The different analyses indicate that the scenario that would best meet the set objectives while being economically viable is one with solid development of renewables, storage capacities, and demand management while retaining a significant share of nuclear power. Emmanuelle Macron's recent announcement of the construction of 6 EPRs indicates that the most likely scenario is one in which nuclear power production remains significant (ECO, 2023). Probably around 40 GW of installed capacity, compared with 61.4 GW today. It would represent around 35% of total production over the year, considering the load factors of the various technologies (RTE, 2022-2).

3.3 Discussion of the challenges

Whatever scenario is adopted between now and 2050, the challenge for the grid remains the same: to ensure that supply equals demand. It means meeting demand in terms of overall quantity over the year. But it also requires the ability to regulate supply or demand so that both remain equal at all times. Decarbonizing electricity production implies shutting down gas-fired power plants, currently the primary controllable power plants. The massive introduction of renewable energy does not affect CO2 emissions if fossil plants are used to back up renewable power plants (PERCEBOIS et al., 2019). Today's gas-fired power plants enable substantial variations in production over short periods (less than an hour). Hydropower plants with dams are the only renewable power plants with this level of control, and they do not have sufficient capacity to absorb all variations in demand. It is clear that in the future, production will not be able to be modulated as it is today, so other solutions will have to be found. For example, we can expect demand to be increasingly controlled to match supply. But also, that energy storage and interconnection capacity will increase. Furthermore, the increase in the share of renewable energies will lead to a decentralization of energy production, mainly due to the development of photovoltaics on small surfaces.

The French electricity sector, therefore, faces the challenges of flexibility and decentralization (LEBROUHI et al., 2022). This section will take a closer look at these challenges and discuss proposed solutions.

3.3.1 Smart Grid

The growing share of intermittent renewable energies will considerably increase the need for energy storage capacity. However, smart grid management will help limit this need for storage (PERCEBOIS et al., 2019). The idea of the Smart Grid is to manage demand in real-time to avoid peaks in demand or peaks in production without a demand.

Today, the power grid mainly transmits and distributes electricity from a few large production centers (more than 60% of the electricity produced in just 18 nuclear sites) to end consumers spread across the country. The development of renewable energies will considerably decentralize production, and this can lead to grid congestion, as is currently the case in Germany (LEBROUHI et al., 2022). Furthermore, the integration of electric vehicles will increase demand for charging stations. The smart grid is, for example, a means of controlling charging stations to match renewable production.

Smart grid development involves integrating technologies such as artificial intelligence and blockchain into the grid to optimize and forecast production and consumption in real-time (LEBROUHI et al., 2022). But it also means installing a network of smart sensors on the grid to transmit information and physically control consumption. To this end, Enedis has been deploying Linky-communication meters in France since 2010. The purpose of these meters is to provide the network with real-time information on consumption. Other projects are currently being tested and developed in various French cities (LEBROUHI et al., 2022). These smart meters raise questions about the control of information and privacy protection. When the Linky meters were first installed in France, there were some opposition movements. This opposition probably comes from a lack of knowledge and confidence in energy policies. It highlights that to develop a smart grid in which consumers are willing players, clear legislation on data control needs to be put in place. Furthermore, consumers must be educated and trained to understand what is at stake in these transformations.

3.3.2 The electrification of transport

The electrification of transport has already begun in Europe with the sale of electric cars. It is set to increase further with European legislation banning the sale of new combustion engine cars by 2035. The market grew by 108% between 2020 and 2021. The targets for 2050 are 95% electric private cars and 20% electric buses and trucks (RTE, 2022-2). In France, there are still limits to the development of electric cars, particularly the lack of public charging points and the virtual absence of fast chargers. Most charging stations are at home; by 2030, an estimated 7 million chargers will be connected to the grid (LEBROUHI et al., 2022). However, this situation is set to change over the next few years to enable better control of demand for these charging points.

The electrification of transport is a challenge, as it is one of the main factors behind the increase in electricity consumption, along with the electrification of industry and heating. Transport is expected to consume around 100 TWh of electricity by 2050. However, electric cars also represent an opportunity for grid management and smart grid development. Indeed, if the grid can control charge points and access user needs information, it can set up smart charge management (LEBROUHI et al, 2022). It means vehicles will be charged when production is highest and demand lowest. This management can be achieved by direct control of charging points. The challenge of smart charging is to automatically modulate charging power to minimize peaks.

Vehicle-to-grid (V2G) integration can go even further. In V2G integration, grid-connected vehicle batteries are used as storage. Production peaks are stored in the vehicle's batteries (G2V), and charged batteries are used for demand peaks (V2G). It can also be done locally with intelligent and bidirectional charging stations, where vehicles can transfer their energy not only to the grid but also directly to another vehicle or building connected to the charging station (LEBROUHI et al., 2022). With this bidirectional battery concept, the purchase price of the battery would be divided between its use for mobility and energy storage (PERCEBOIS et al., 2019). It would include financial compensation from the grid to the user for using his battery.

Integrating electric vehicles into the smart grid will be necessary in the coming years. If electric vehicles remain passive users, as they are today, demand could destabilize the grid. However, if their capacities are used, they can be an advantage for the grid, with V2G capacity estimated at 1.7 GW in 2050 (RTE, 2022-2).

3.3.3 Energy storage:

Energy storage will be a necessity to ensure flexibility on the grid. Various technologies in use today or under development can provide flexibility over different periods. Batteries can provide daily to weekly flexibility (BONIN et al., 2019). STEP pumped storage systems, compressed air energy storage (CAES), and power-to-gas (P2G) conversions enable energy to be stored over more extended periods and thus can provide seasonal flexibility. But all these storage systems have a cost that adds to the cost of producing electricity (PERCEBOIS et al., 2019). Furthermore, of all these systems, only STEP and batteries are already implemented in France, so these systems must prove their technical functionality and economic benefits (LEBROUHI et al., 2022). The future will lie in combining these different energy storage systems.

We saw in the EV section that vehicle batteries must be used in V2G. However, the various RTE scenarios also call for increased installed stationary battery capacity, up to 26 GW, in the nuclear-free scenario. This increase represents a significant challenge, as global installed capacity currently stands at just 10 GW, and in France, only 0,5 GW in 2022 (RTE, 2022). PERCEBOIS and POMMERET (2019) estimate in their article that the mean cost of a battery power station is 16 €/kWh/year for lithium-ion batteries. Batteries could therefore be a viable option if the cost of renewable energies is below that of thermal power stations and if these batteries replace these power stations during peak periods (BONIN et al., 2019). Lithium-ion batteries have a fast charging capacity and high energy density, enabling flexibility (PALISBAN and KAUHANIEMI, 2016). The problem is that large quantities of lithium are needed to produce these batteries, which are not available locally. Therefore, the challenge is to develop battery recycling to limit the ecological impact. Unfortunately, batteries cannot store energy efficiently over long periods and respond to challenges such as several weeks without wind or the seasonal production gap (RTE, 2022-2). Other systems will also have to be implemented.

Pumped energy transfer stations (STEP) are currently the most developed storage technology in use in France, with a capacity of 4.2 GW in pumping (LEBROUHI et al., 2022). The aim is to develop this technology to 8 GW by 2050 (RTE, 2022-2). It enables long-term storage by filling the reserves of high-mountain dams. This technology is already well established and marketed worldwide and has the advantage of high storage capacity and efficiency of between 70 and 85% (PALISBAN and KAUHANIEMI, 2016). The problem is that it can only be implemented on a hydropower plant with a large reserve. The only way to increase STEP storage in France is to equip existing dams with pumping stations, as building new large dams is not an option.

Compressed air energy storage (CAES) systems are another solution for the future of energy storage. The principle is to compress air to a pressure of 70 bar and use the energy from decompression in a gas-fired power plant to produce energy. Today, only two plants are in operation worldwide. This technique enables energy to be stored over the long term, in large quantities, with an efficiency of around 70% (PALISBAN and KAUHANIEMI, 2016). Another advantage is its relatively short response time. The problem is that this technology is expensive and requires a lot of storage space. Plants in operation use natural rock cavities as storage space. Furthermore, as this technology is not widely used, it still requires further development. Europe has launched several research programs in this field, and we can expect CAES to contribute to energy storage by 2050 (RTE, 2022-2).

The most promising option for storing energy over long periods and in large quantities is the P2G or gas-to-power (G2P) process. It involves using electrical energy to produce decarbonated gas, which is then used in a decarbonized thermal power plant (LEBROUHI et al., 2022). The two gases used in these technologies are methane from methanation and hydrogen from water electrolysis. Methane would be a good solution on a large scale because hydrogen requires adaptation of the gas network to high pressures of around 100 bars (PERCEBOIS et al., 2019). However, the France 2050 report shows that France is committed to developing its hydrogen production capacity as a priority (RTE, 2022-2).

Indeed, all the scenarios forecast a significant share of electricity dedicated to hydrogen production by electrolysis. This hydrogen could be used directly as a fuel in industry and transport. It could also be used to generate electricity in decarbonated gas-fired power plants. However, this is a significant challenge, as the industry is virtually non-existent in France; only 6% of hydrogen is produced by electrolysis (LEBROUHI et al., 2022). The creation of this hydrogen economy requires substantial investment in hydrogen production and power plant construction, as well as the creation of a network since hydrogen has a low energy content and must therefore be transported at high pressure to produce energy. However, France has an advantage, with the Hydrogène de France (HDF) company at the forefront of hydrogen technologies, notably with the development of high-power fuel-cell production plants (HDF, 2023).

3.3.4 Interconnection

Another challenge we mentioned in Part II is the development of interconnections. Electrical interconnection is essential, as it enables us to compensate for variations in intermittent renewable sources by combining them at a European level. It also reduces the cost of their integration by mutualizing reserves and sources of flexibility (LEBROUHI et al., 2022). The target described in Futur 2050 is 39 GW of interconnection capacity between France and its European neighbors (RTE, 2022-2).

In 2019 RTE proposed a plan to build new interconnections. These interconnections were divided into 3 packages. Package 0 for interconnections already under construction or development. Package 1 for projects that have not yet begun but are certain to see completion, and Package 2 for more uncertain projects. The projects in packages 0 and 1 alone represent an increase of 10 GW in capacity (CRE, 2020). These 2 packages include the Celtic project, the first power cable between France and Ireland (scheduled for 2027), the Savoie-Piémont project to reinforce exchanges with Italy (partially commissioned in 2022), and the Golfe de Gascogne project with Spain (scheduled for 2027) (RTE, 2022-1).

3.4 Markets to encourage the transition

The grid is the key player in the energy transition and must adapt to continue to meet its objective of equalizing supply and demand. However, the challenges outlined above also call for market evolution. Markets must accompany the transition and be tools for achieving the objectives set by the government. The idea is to increase France's ability to plan energy production over the long term (FINON, 2020).

Indeed, the current energy transition differs from other energy transitions, such as the switch to nuclear power in the 1970s. The aim is not to develop cheaper, more efficient technologies. On the contrary, it is to install intermittent sources of renewable energy, which are currently more expensive than the other solution. The social objectives of reducing emissions are the priority, not the economic objectives of reducing costs (MILLOT et al., 2020).

Measures have already been taken in recent years to correct the initial market, such as introducing a capacity market and developing AOLT. These reforms already have a positive impact but need improvement.

3.4.1 Reform of the carbon quota market

In 2005 the European Union introduced carbon quotas. Each country is entitled to a certain number of tons of carbon emitted. Every year, these quotas are reduced in line with emission reduction targets. These emissions are divided between various industries, including the carbon-based power generation industry (ECO, 2023). These carbon quotas are then traded on a CO_2 permit market where the prices fluctuate. As a result, this market does not send a stable long-term signal of a high price per tonne of CO_2 (FINON, 2019). Even worse, the primary CO_2 emitters industries made billions of profits by trading in the CO_2 market (LE MONDE, 2023). A reform of the CO_2 quota mechanisms is needed, which will eventually lead to a stable increase in the price per tonne of CO_2. This reform will lead to higher costs for producers of carbon-based electricity and, therefore, a willingness to invest in renewable energies or storage capacity. Without this, it will be difficult to trigger significant investment in low-carbon technologies (MILLOT et al., 2020).

The European Parliament is currently discussing a reform of Objective 55 to make carbon quotas more effective and to make it possible to control the CO_2 trade market.

3.4.2 Public subsidies

Another essential measure is the development of AOLT. The aim is to secure a price for renewable electricity a private investor produces. Today, the need is to increase AOLT contract share (FINON, 2019). To do this, the State needs to increase the guaranteed price for the electricity produced. This augmentation will enable private investment in more expensive technologies like offshore wind turbines or carbon-free gas-fired power plants. The State must ensure the long-term profitability of renewable energies for private investors.

In his 2019 article, FINON proposes the creation of a central body that would be in charge of these calls for tender and would therefore be a planner of the future grid. This planner would have to decide how high and when to trigger auctions for long-term contracts by renewable energy or storage technology. Furthermore, it would have to respond to government objectives through this planning. It would separate long-term investments decided by this national planner from short-term markets. This double policy is already implemented in South American countries and has positive results. Today, the AOLT is determined with a single price for all technologies directly by the Ministry of Ecological Transition.

If the long-term tendering mechanism succeeds in enabling a massive integration of electricity storage systems over the next few years, it could reduce one of the problems of the SPOT market, which is the correlation of spot energy prices with gas prices. Indeed, if batteries are discharged into the grid during peak consumption, this could replace the need for gas-fired thermal power plants and, thus, lower the electricity cost.

3.4.3 A legal framework for energy communities

Energy communities are a concept developed by Scandinavian countries and are now taken up and developed by European authorities. The idea is that consumers can group together to become network players by investing together in electricity production capacity (VERNAY, SEBI, and ARROYO, 2023). For example, an association of neighbors in a street might decide to finance the installation of solar panels on all the homes in the area. Or an agricultural cooperative choosing to install wind turbines in their fields. The idea is for a group of citizens to come together to produce enough power to be sold to the grid and to achieve economies of scale on the installation. The future of energy communities is to be integrated into the smart grid, so they can produce for the grid but also absorb demand with storage capacity, for example.

The idea behind energy communities is to make citizens players in the energy transition. It will help to increase the number of renewable energy installations, mobilize private capital, limit the need for public investment, and educate and empower consumers (VERNAY, SEBI, and ARROYO, 2023).

To achieve this, France must create a legal framework allowing community energies to enter the electricity market. Furthermore, create actions that encourage and spread this form of grid integration—for example, public subsidies or loans at guaranteed rates.

4. Conclusion

In conclusion, we examined how the French electricity sector is organized today, the history of grid development, and how the electricity market works today. This analysis led us to look at the scenarios RTE produced for 2050 and the challenges that will arise to bring this energy transition to reality. These challenges are the electrification of the economy and the massive integration of renewable energies into the energy mix. The grid must adapt for the massive integration of non-dispatchable renewable generation sources to be possible. These adaptations include

- Increasing storage capacity
- Managing electricity demand
- Increasing interconnections on a European scale.

For the market to really encourage these transitions, the State and Europe must:

- Increase the price and better manage carbon quotas
- Increase subsidies and further develop AOLT
- Develop and find a legal framework for energy communities.

RTE's scenarios are based on the government's ability to achieve its objectives and those of Europe and the ability of each citizen to play a part in this transition. Every one of us, therefore, has responsibilities in the future of energy. The first responsibility is to elect political representatives who take these issues seriously and make the right decisions. The second responsibility is to be a player in this transition by informing those around us about the issues at stake and by consuming more responsibly (type of transport used, type of heating, insulation of homes, installation of solar panels, etc.).

This work focused on the electricity sector and the difficulties it will face in making an energy transition that meets climate objectives. But this is only one aspect of the energy transition, and we could also have looked at other aspects. For example, energy efficiency is an essential issue in this transition, as is the development of biofuels. Our analysis could also have been extended to other European Union countries in the same electricity market.

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