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State or Market: Investments in New Nuclear Power Plants in France and Their Domestic and Cross-border Effects

by Florian Zimmermann and Dogan Keles

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State or Market: Investments in New Nuclear Power Plants in France and Their Domestic and Cross-border Effects

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Abstract:

France wants to become carbon-neutral by 2050. Renewable energies and nuclear power are expected to make the main contribution to this goal. However, the average age of nuclear power plants is approaching 37 years of operation in 2022, which is likely to lead to increased outages and expensive maintenance. In addition, newer nuclear power plants are flexible to operate and thus compatible with high volatile feed-in from renewables. Nevertheless, it is controversially discussed whether nuclear power plants can still be operated competitively and whether new investments will be made in this technology. Using an agent-based simulation model of the European electricity market, the market impacts of possible nuclear investments are investigated based on two scenarios: a scenario with state-based investments and a scenario with market-based investments. The results of this investigation show that under our assumptions, even with state-based investments, carbon neutrality would not be achieved with the estimated nuclear power plant capacity. Under purely market-based assumptions, large amounts of gas-fired power plants would be installed, which would lead to an increase in France's carbon emissions. State-based investments in nuclear power plants, however, would have a dampening effect on neighboring spot market prices of up to 4.5 % on average.

Keywords: France; nuclear; electricity market; capacity remuneration mechanism; cross-border effect; investment

Highlights:

- An agent-based electricity market model is applied with a focus on the French market
- Two scenarios are simulated: market-based vs. state-supported nuclear investments
- New investments in nuclear power plants simplify the path to net zero in France
- State-based nuclear investments cut prices and emissions in France and nearby markets
- Market scenario does not enable substantial investments in nuclear power in France

State or Market: Investments in New Nuclear Power Plants in France and Their Domestic and Cross-border Effects

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Abstract

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1. Introduction

In France, carbon emissions in the energy sector are low (291 Mt in 2019) compared to other similarly developed countries, such as Germany (663 Mt in 2019) (Eurostat, 2021). A major reason are the 61.3 GW of installed nuclear power capacity in 2020 (IAEA, 2021), which accounts for a significant share of the country's electricity (70.6 % of the electricity produced in France) and heat production. Nevertheless, carbon emissions will have to fall even further, as France has committed to the climate neutrality target (see French Government, 2017, 2020).

The French government has set energy policy objectives with the *Plan Climat* (French Government, 2017) and the national climate plan (French Government, 2020). For example, carbon emission neutrality is to be achieved across all sectors by 2050. Furthermore, the plan provides that the share of nuclear power in electricity generation is to be reduced to 50 % by 2035 (still maintaining a high proportion of nuclear power plants for electricity generation), and at the same time 33 % of electricity is to be generated from renewable energy sources (RES) by 2030 (French Government, 2020).

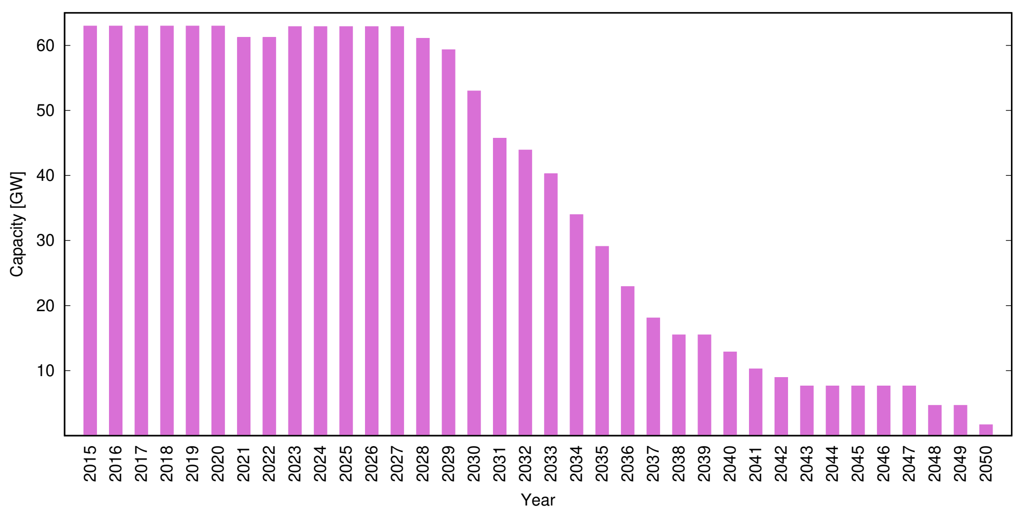

Figure 1: Nuclear installations in France and possible shut down with an estimated lifespan of 50 years. Construction year based on S&P Global Platts (2016) and own research.

The power plant fleet in France will reach the limits of its technical lifetime in the near future. Coal-fired power plants are already scheduled for decommissioning by 2022. The nuclear reactors are approaching an age of 37 years on average (as of March 2022) and produce electricity without carbon emissions. Figure 1 shows the nuclear capacity development in France for an assumed technical lifespan of 50 years. The first power plants subject to concrete measures for decommissioning were Fessenheim I and II; both units were shut down mid 2020.

The relatively old power plant fleet causes some challenges. The susceptibility to faults, partly due to the use of non-compliant spare parts and a lack of spare part availability, and the power plant failure rate are increasing in France (Wealer et al., 2021b, and Autorité de Sûreté Nucléaire, 2021, p. 297). Due to the units' age, maintenance intensity is expected to continue to increase, which will also raise the costs (Autorité de Sûreté Nucléaire, 2021, p. 297).

Due to the increased integration of intermittent RES, such as wind and photovoltaics, higher standards are required for the complementary power plants, especially in terms of flexibility. The Nuclear Energy Agency (2012) states that old nuclear power plants are not suited to provide great flexibility and cannot be operated economically below 50 % of the nominal load over a longer period of time. However, new power plants could be operated much more flexibly. Therefore, the extension of the lifetime of operating nuclear power plants appears not to be a suitable solution in order to support the electricity system with flexibility in the future.

Nevertheless, nuclear power plants are an essential pillar of the French energy system strategy for meeting the target of carbon neutrality (French Government, 2017, 2020). Therefore, investments in the nuclear power plant fleet will have to be made in the near future to build new plants or to extend the technical lifetime of existing ones.

In 2017, the French government took the opportunity to introduce a capacity market in order to, among others, incentivize investments in new flexible power plants and reduce risks for investors in order to stabilize generation adequacy. However, investments in nuclear power plants seem to pose considerable risks in terms of height and completion. These risks are particularly evident in the construction of new power plants in Flamanville, which is currently the only reactor under construction in France, Hinkley Point (United Kingdom), and Olkiluoto (Finland). For example, the expected investments can be almost six times higher (Bloomberg, 2020; World Nuclear News, 2012) than originally planned and there are delays in construction of more than 10 years (TVO, 2008, 2021).

Also, Roques et al. (2006) or Boccard (2014) raise the fundamental question of whether nuclear power plant investments can be economically advantageous in today's market environment. Both see economic challenges in operating nuclear power plants in competition with RES.

Not only energy policy considerations, but also security policy considerations seem to be driving the use of and investment in nuclear capacities. The strategic security policy consideration is one aspect that further explains the announcement of plans to build six new nuclear power plants and to extend the technical lifetime of the existing plants as far as possible (Wakim, 2019; Reuters, 2019, 2022).

The challenges and risks identified raise the question of how much the market would contribute to stimulating the necessary investments in order to achieve the goal of carbon neutrality. Research question (RQ) 1 therefore reads as follows: Can the current market design in France trigger the required investments in nuclear power plants or is additional support necessary?

However, decisions on investments in France (either market-based or state-supported) not only affect the domestic market, but can also be expected to generate relevant effects on neighboring countries due to the closely coupled spot electricity markets in central Europe. A market characterized by low-carbon technologies (i.e., nuclear power) that can supply electricity almost independently of the EU emission trading scheme can have an impact on neighboring market areas that are characterized by higher shares of carbon-intensive production technologies (e.g., coal, gas), such as Germany, and thus high spot market prices.

These so-called cross-border effects of different technologies and market regulations on prices or investments in coupled markets have been studied broadly in the literature (see, e.g., Bhagwat et al., 2014, 2016, 2017). Some studies focus on European countries, such as Switzerland (Zimmermann et al., 2021; Keles et al., 2020), Germany (Annan-Phan and Roques, 2018; Rinne, 2019), or Italy (Bianco and Scarpa, 2018), all of them having large trading capacities of electricity with France. However, there are hardly any studies focusing on the cross-border effects of existing and, particularly, new nuclear investments on the neighboring markets, especially considering the interplay with and strong increase in renewable power in these markets. France serves here as an extraordinary example. Given the impact of non-market-driven investments, the distortions in neighboring markets are of particular interest. RQ 2 therefore reads as follows: What are the spillover effects resulting from nuclear investments in France on strongly coupled electricity markets in different investment scenarios?

The two research questions will essentially be examined in more detail in this paper. In the next part (Section 2), we will give a short overview of which scientific studies have already been carried out of the problems pointed out. In the following, we introduce the underlying methodology (Section 3) as well as the input data (Section 3.4). In order to answer the questions, this is followed by a detailed presentation of the results (Section 4.2) of the scenarios investigated focusing on investments in flexible power plants, price development, cross-border flows, and carbon emissions. Subsequently, Section 5 discusses the key findings and, moreover, contains a critical analysis of the results and an assessment of the study's limitations. Finally, conclusions will be drawn and policy measures will be derived from the findings (Section 6).

2. State of the Art

Basically, there is a large literature on energy system analysis and on investments in new power plants, especially in the context of increasing RES shares to achieve decarbonization targets. For instance, Hainsch et al. (2021) examine different decarbonization pathways for Europe and the implications for the electricity system.

The question of investments in nuclear power plants has been investigated less frequently in the past. For example, a paper on achieving a carbon-free power system in 2035 was prepared for Finland, with the investigation of investments in RES, but with exogenous nuclear scenarios (Koivunen et al., 2020).

Far more questions are being addressed with regard to the decommissioning of nuclear power plants. This development had been accelerated especially after the Fukushima accident. As a result, a number of case studies were produced on the effects of a nuclear phase-out. For example, there are papers for Belgium (de Frutos Cachorro et al., 2020, 2019; Laleman and Albrecht, 2016; Kunsch and Friesewinkel, 2014), Germany (Bruninx et al., 2013), Japan (Hayashi and Hughes, 2013; Komiyama and Fujii, 2015), Switzerland (Pattupara and Kannan, 2016), Sweden (Andersson and Hådén, 1997; Kan et al., 2020), or for larger regions, such as North America, Europe, and Japan (Glomsrød et al., 2015). The analytical investigations of the papers are diverse, covering, e.g., generation capacity investments, generation mixes, greenhouse gas emissions, or electricity prices.

Studies examining 100 % RES scenarios (e.g., IEA and RTE, 2021) implicitly assume a nuclear phase-out if previously installed capacity has existed. An overview of different studies regarding 100 % RES in the electricity system can be found in Heard et al. (2017), who are rather skeptical about the economic feasibility of these scenarios. However, Brown et al. (2018) come to a much more optimistic conclusion about the technical and economic feasibility.

Nuclear phase-out scenarios for France have also been studied, for instance, by Malischek and Trüby (2016) highlighting the resulting costs to the national economy. To estimate the need for network expansion, the European Network of Transmission System Operators for Electricity (ENTSO-E) regularly studies comprehensive policy-related scenarios (e.g., ENTSO-E, 2020). These studies are all based on studies of local TSOs. For France, the transmission system operator RTE (2021) prepares long-term scenarios with the aim of converting the energy supply into a carbon-neutral system. For this purpose, a total of six scenarios were examined with variation of the shares of solar, wind onshore as well as offshore, and nuclear power. One of these scenarios was completely designed without nuclear capacities, but with 100 % RES in 2050. Other scenarios assume a remaining nuclear capacity of 16-24 GW in 2050. New installations vary from 0-28 GW of installed nuclear capacity in these scenarios. An overview of the assumptions of the nuclear capacity development in different studies can be found in Table B.17 in the Appendix. However, as in Koivunen et al. (2020) for Finland, the focus is not on the economic investments in flexible, especially nuclear power plants, but rather on the technical feasibility and security of supply.

Another approach is to retrofit the existing nuclear fleet in France with the aim of a robustly and cost-optimally determined path proposed by Perrier (2018). Maïzi and Assoumou (2014) investigate investments in France under three different nuclear policy scenarios (normal shut-down, lifetime extension, retrofit) but without explicit consideration of the coupled neighboring markets.

Shirizadeh and Quirion (2021) examine the cost-optimal electricity mix in France under different carbon price paths including investments in new nuclear capacities. The cost-optimal electricity mix and the security of supply in France were studied by Alimou et al. (2020). However, both studies completely neglect the neighboring countries and the relevant interdependencies. The impact on the security of supply of different penetration rates of RES in France was also studied by Krakowski et al. (2016). Again, the costminimal expansion was calculated (i.e., not necessarily the market-driven investments) without the detailed modeling of the neighboring countries.

The studies that do not take into account neighboring countries neglect important effects. The close coupling of markets and the high interconnectivity between France and neighboring countries can lead to significant cross-border effects, which have been investigated in several studies. Theoretical investigations have been carried out by, e.g., Lambin and Léautier (2019); Bhagwat et al. (2014, 2016, 2017), or Lautier (2016). In case studies, cross-border effects have been analyzed between the French and Swiss energy markets with a focus on prices (Dehler et al., 2016; Keles et al., 2020) or in future scenarios without (Pattupara and Kannan, 2016) and with consideration of CRMs (Zimmermann et al., 2021). Cross-border effects between Germany and France based on wind generation have been studied by Annan-Phan and Roques (2018). The level of influence of nuclear power plants in France or, in particular, their absence from the market (due to maintenance or outage) on German electricity prices is addressed by (Rinne, 2019). The influences between France and Italy, taking into account different nuclear reactor decommissioning plans, are further explored in Bianco and Scarpa (2018). Glomsrød et al. (2015) examine electricity price changes in neighboring countries due to the German nuclear phase-out.

While most publications highlight a nuclear phase-out and look at the aspects from different perspectives, there is no analysis of the premise of how markets behave with a governmental nuclear policy or a market-driven investment activity. We will study the effects of governmental policy or market-driven investments on the domestic and neighboring markets based on the example of France, as it is an extraordinary case of nuclear power investments together with RES power expansion at the same time.

3. Agent-based Simulation Model

In this section, the methodology based on a power market model for the French electricity market and the neighboring countries is presented. The research questions require an investigation of investment decisions in flexible power plants in the electricity sector with a high degree of technical detail. Therefore, the choice of methodology according to the categorization by Herbst et al. (2012) falls into the area of bottom-up models, which allow a high level of detail, such as different power plant technologies, their respective efficiency, and the detailed demand and renewable generation profiles.

Since the investment decisions are to be investigated under specific market conditions, the optimization models, which are widely used in energy economic research, turn out to be rather unsuitable for dealing with this issue, since they usually formulate tight constraints and determine an optimal set under - mostly - minimum costs (e.g., which is the cost optimal power plant park in 2050 under carbon neutrality). However, this paper addresses the behavior of investors in liberalized electricity markets with the possibility of stranded investments (not under optimal conditions). This study requires the consideration of possible market failures, for which fundamental optimization models are not suitable. Therefore, we decided to use power market models deploying agent-based simulation.

Subsequently, the agent-based electricity market model PowerACE was extended and applied with a focus on France including capacity markets in the respective market areas.

3.1. Overview of PowerACE

The PowerACE model has already been used in other analyses and has been described in detail in (e.g., Zimmermann et al., 2021; Ringler et al., 2017; Keles et al., 2016; Bublitz et al., 2015). An advantage of agent-based simulation models is their ability to reflect investment uncertainties and imperfect markets (Ventosa et al., 2005). Therefore, the approach is highly suitable for the investigation of price developments and investment decisions in different market areas.

The main difference in the investigation (compared to the above-mentioned studies) is the spatial expansion of the market areas. Therefore, the new version of the model includes the market areas of Austria, Belgium, Czech Republic, Denmark, France, Germany, Great Britain, Italy, Luxembourg, the Netherlands, Poland, Portugal, Spain, and Switzerland. If one of these markets is going to introduce or has already implemented a capacity remuneration mechanism (CRM), this is implemented in the model as well.

The model simulates the day-ahead spot market with an hourly resolution including a welfare-maximizing market coupling approach. This optimization is subject to limited net transfer capacities (NTC) between all simulated market areas (based on Ringler et al., 2017).

The bids for the day-ahead market are prepared by different types of agents representing the market participants (depicted in Figure 2). Thus, for each country, one demand agent exists to procure the complete hourly electricity demand of all sectors. One agent offers the total supply of RES to

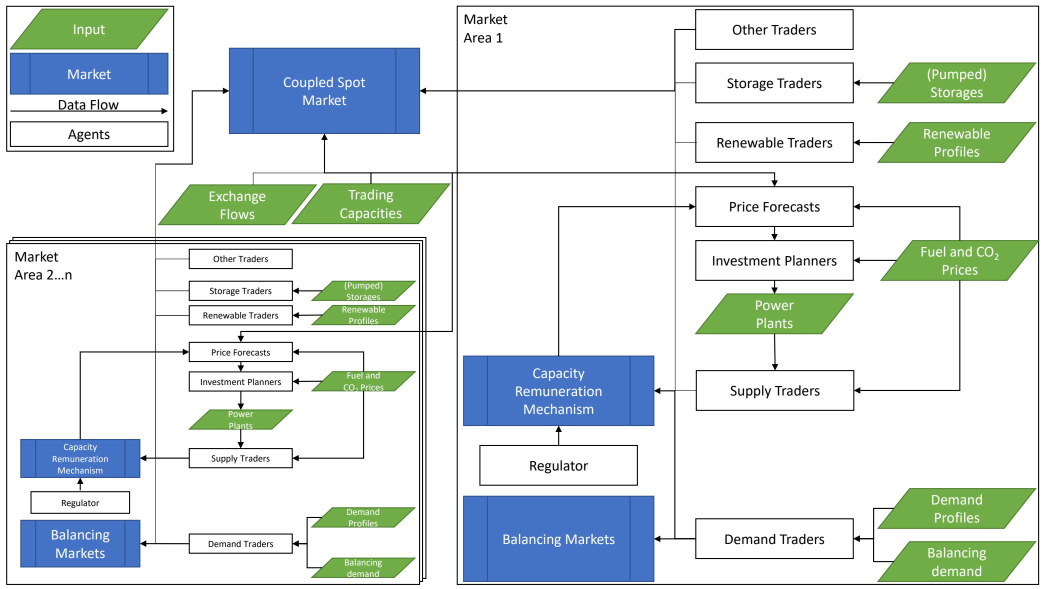

Figure 2: Schematic overview of the main parts of the electricity market simulation model PowerACE.

the market. Several agents represent power plant operators that offer power plants to the market mainly based on variable costs, i.e., fuel and carbon prices, the techno-economic parameters of the power plants, and a mark-up to cover fixed costs and investment expenditures. There are also agents for pumped storage or battery storage that create load-balancing hourly bids for charging and discharging (or pumping and turbining).

Main input data are hourly renewable energy production profiles, conventional power plants (including their techno-economic characteristics), hourly electricity demand, yearly net transfer capacities, start-up costs, fuel prices and prices for carbon emission certificates. The implementation of the French CRM as well as the implementation of hydropower specifics (especially for Switzerland) are described in more detail in Zimmermann et al. (2021).

3.2. Investments in Generation Capacity

Conventional power plants are decommissioned due to age or on the basis of nuclear or coal phase-out strategies of the countries (e.g., Germany). This results in a need for new capacities. Therefore, in each simulated year within the selected time horizon, supply agents evaluate the feasibility investments in new flexible power plants considering also options to expand or reinvest power plant capacity. Investment options are exogenously specified using techno-economic data on their efficiency, construction time, capital expenditures, annual fixed costs, and fuel-independent variable costs. Investment decisions are based on a net present value (NPV) calculation for each market area using expected future cash flows from various market segments and the capital as well as fixed costs. Potential cash flows of the power plants can arise both from the sale of electricity on spot markets and from participation in CRMs depending on the respective market area configuration. The cash flows from the sale of electricity are calculated using an electricity price forecast for the respective wholesale spot markets. The price forecast takes into account possible future electricity demands, RES feed-in and NTC development, as well as the development of carbon certificate and fuel prices in the following years. This input data is from different resources (see Section 3.4). In addition, estimated revenues from the CRMs are also included in the calculation of the NPV.

All investment options are evaluated over all market areas using the NPV method over a period of half of the technical lifetime or a maximum of up to 20 years. Once a specific NPV has been determined for each power plant option in each market area (based on the data previously described), the option with the highest positive NPV is invested in. An additional price forecast is calculated, which takes into account the power plant to be invested in, and the NPV is determined again. If the NPV is still positive, the investment is made in this option in the corresponding market area. The additional price forecast is intended to prevent the power plant from cannibalizing its own positive cash flows. This procedure is repeated until no investment option with a positive NPV exists for the year under consideration in any market area (Figure 3). (Zimmermann et al., 2021)

The electricity price forecast deploys a similar simulation as the spot market simulation described above and is carried out annually when evaluating new power plant investments. However, some simplifications are made in order to save computing time. For example, the price forecast is calculated for a maximum of 10 years in the future, as otherwise the uncertainties would be in unfavorable imbalance with the additional calculation time. When the end of the period under consideration is reached, the values are constantly extrapolated. During the price simulation, the development of the installed power plant capacities (investments and decommissioning) is considered up to 5 years into the future in order to neither overestimate nor underestimate future capacity requirements. The variable costs, however, will be adjusted

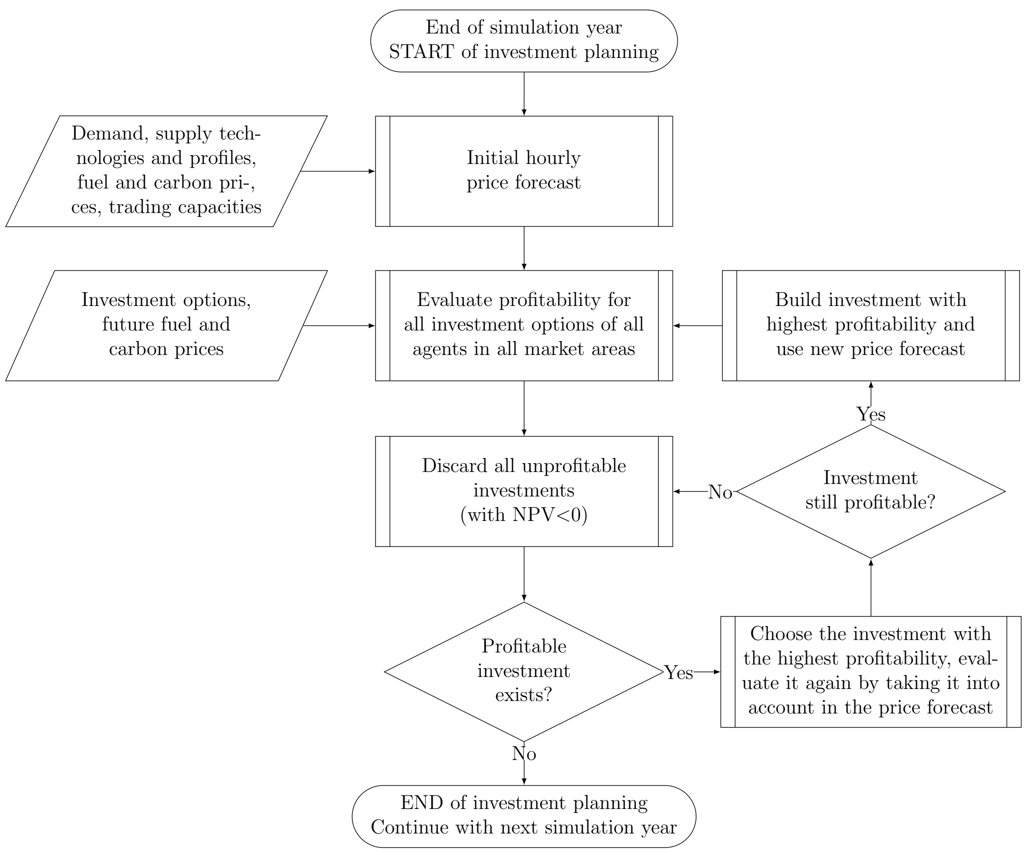

Figure 3: Simplified schematic process overview of investment planning in PowerACE.

even after these 5 years based on the fuel and carbon price scenario. In addition, the hourly average of the startup costs and the realized mark-up per market area are added to the variable costs. Finally, to reduce the complexity of the model, a new price time series is calculated for every two years in the future. For the years not considered, the following year's forecast is used for the NPV calculations in order not to be subject to a conservative expansion of the power plants.

In the European context, electricity market coupling plays an important role that can lead to cross-border effects. These effects can have a strong impact on market prices and therefore also substantially affect the profitability of investments in a liberalized market environment. In order to take cross-border effects into account and to consider interdependencies between different market areas, the following optimization problem (based on Ringler et al., 2017) is solved every two years for each hour of the year to receive the hourly price forecast for each market area m:

Target function

$$\max_h : \sum_{m \in M} [(\sum_{d \in D_{m,h}} p_d \cdot Q_d \cdot q_d) - (\sum_{s \in S_{m,h}} p_s \cdot Q_s \cdot q_s)] \quad \forall h \in H \tag{1}$$

subject to

$$0 \leq q_s \leq 1 \quad \forall s \in S_{m,h} \quad \forall m \in M \quad \forall h \in H \tag{2}$$

$$0 \leq q_d \leq 1 \quad \forall d \in D_{m,h} \quad \forall m \in M \quad \forall h \in H \tag{3}$$

$$\sum_{d \in D_{m,h}} (Q_d \cdot q_d) + \sum_{in \in M'_{m,h}} (E_{m \to in}) = \sum_{s \in S_{m,h}} (Q_s \cdot q_s) + \sum_{out \in M'_{m,h}} (E_{out \to m}) \quad \forall m \in M \quad \forall h \in H \tag{4}$$

$$0 \leq E_{out \to in,h} \leq E^{max}_{out \to in,h} \quad \forall out, in \in M \quad \forall h \in H \tag{5}$$

where

Decision variables

q	Acceptance rate
$E_{out \rightarrow in}$	Exchange flow from market area *out* to market area *in*

Parameters

p	Bid price
Q	Bid volume
$E^{max}_{out \rightarrow in}$	Maximum exchange flow from market area *out* to market area *in*

Indices

h	Considered hour
d	Demand bid
s	Supply bid
m	Market area
out	Exporting market area
in	Importing market area

Sets

M	Simulated market areas (remain constant over the whole simulation)
M'_m	Market areas connected to market areas m
D_m	Demand bids of market area m
S_m	Supply bids of market area m
H	Hour of the price forecast time horizon

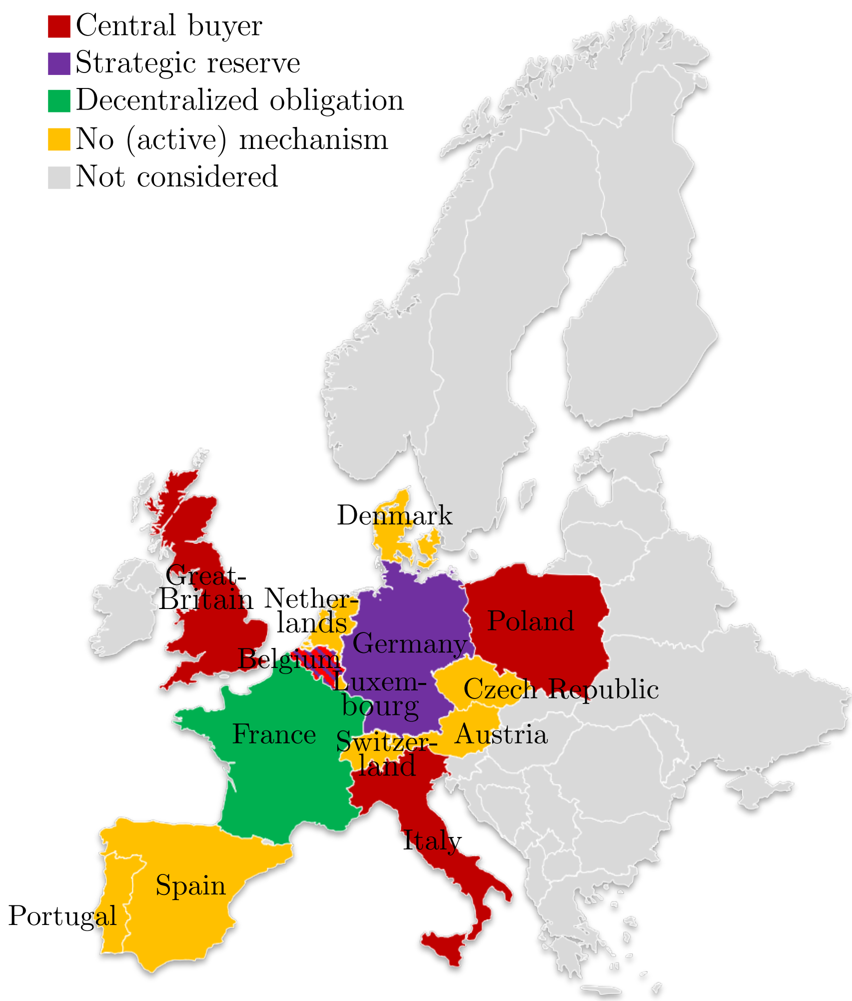

Figure 4: Simulated market areas based on Bublitz et al. (2019); ACER/CEER (2021); Elia Group (2021).

Market designs in countries are subject to ongoing changes and adjustments, often against the backdrop of improving RES integration. To ensure long-term generation adequacy (e.g., Bublitz et al., 2019), some countries have implemented CRMs. Due to the strong focus of the study on investment in flexible power plant options, CRMs need to be adequately modeled,

Table 1: Overview of the main data and sources used in all scenarios.

Input data type	Resolution	Sources
Conventional power plants	Plant/ unit level	Based on S&P Global Platts (2016), completed by own assumptions, e.g., regarding the coal phase-out
Fuel and carbon prices	Yearly	ENTSO-E (2020)
Investment options	Yearly	Schröder et al. (2013)
Trading capacity	Yearly	See Table B.18, B.19, and B.20
Electricity demand and RES feed-in	Hourly aggregated per market area	ENTSO-E (2020)

as payments from CRMs can make a significant contribution to covering and refinancing the capital and fixed costs of power plants. The agent-based simulation model considers strategic reserves (SR) as well as decentralized and centralized CRMs, which are described in detail in Appendix A or by Zimmermann et al. (2021) and Keles et al. (2016).

Figure 4 provides an overview of the corresponding modeled CRM types in the modeled countries. France has already implemented a decentralized capacity market. Poland, Great Britain, and Italy (Bublitz et al., 2019), and from 2025 Belgium (Elia Group, 2021) have installed a centralized capacity mechanism. In Belgium until 2024 and in Germany, a SR is applied. All other countries consider an energy-only market over the entire runtime. This is particularly relevant for Spain and Portugal, as CRMs (for incentivizing investments) have been abolished or postponed in these countries. Therefore, CRMs in these countries are neglected in this study (ACER/CEER, 2021; Bublitz et al., 2019).

3.4. Input Data for the Simulation Model

As this study is focused on the French electricity market, the PowerACE model is extended to include countries that particularly have a direct connection to the French grid: Spain and Great Britain. In addition, Germany, Switzerland, Belgium, Luxembourg, the Netherlands, Italy, Austria, Poland, Czech Republic and Denmark were already integrated in the model as described in previous studies (i.e., Zimmermann et al. (2021)). Finally, Portugal, as second major country of the Iberian Peninsula, has been added. All modeled market areas and their assumed CRM are shown in Figure 4.

For the exploratory model runs, large amounts of data are collected, pre-processed in a database, and incorporated into the model (Table 1). The investigation horizon is from 2015 to 2050 in hourly resolution for each year. The key input data is derived from the National Trends Scenario of the Ten-year Network Development Plan 2020 (ENTSO-E, 2020), which provides aggregated annual data for demand and RES electricity production for the reference years 2025, 2030, and 2040 (see Appendix B). To match with the model time horizon, the data is linearly extrapolated to 2050 applying the rate of increase between the given years 2030 and 2040 to the full horizon of investigation. Historical values are based on Eurostat (2020) and the Swiss Federal Office of Energy (2020) for Switzerland. All input data for years between the historical or the reference years are automatically interpolated linearly by the model.

The capacity development of pumped storage power plants as well as that of battery storage is taken from ENTSO-E (2020), Eurostat (2020), and Swiss Federal Office of Energy (2018). For battery storage, the assumption of the size of the storage volume is identical to the symmetrical (dis-)charging capacity.

The flexible power plants are represented block by block on the basis of the power plant database by S&P Global Platts (2016). In addition, further power plants are added to the database on the basis of our own research. Assumptions on techno-economic parameters, start-up costs of the power plants, and the main parameters for investments in new power plants are primarily based on Schröder et al. (2013). The demand for balancing reserve capacity is based on ENTSO-E (2021) and reduces the net output of the installed power plants.

The price developments for carbon certificates are shown in Figure 5 with target prices of 122 EUR/t_{CO_2} and 150 EUR/t_{CO_2}, however, with different paths. The prices for fuels are from ENTSO-E (2020) and are extrapolated linearly from 2040 onwards.

Trading capacities between market areas are based on ENTSO-E (2020) and on German TSOs (2019) for Germany. All non-endogenously modeled markets are considered via static exchange flows based on ENTSO-E (2021).

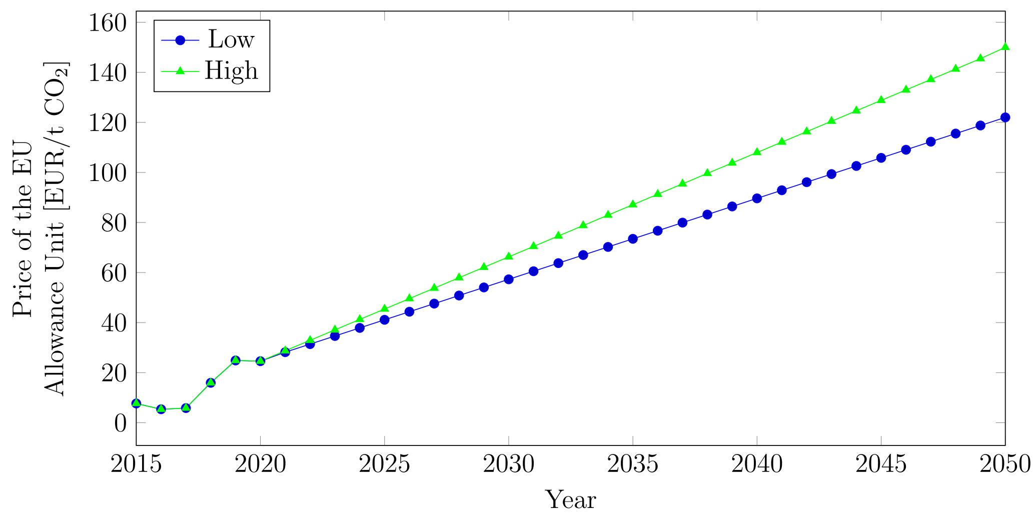

Figure 5: Exploratory development of the carbon price paths. Historically, it is based on the average of the EEX pices until 2019. The prices are linearly interpolated between the historical prices in 2019 and 2050 to the target value of ENTSO-E (2020) (122 EUR/t_{CO_2}) as carbon Low. The High sensitivity is analogously linearly interpolated to the target value of 150 EUR/t_{CO_2}.

4. Results

The research design is described in Section 4.1 and the main results of the study are presented in Section 4.2. In Section 5, a discussion of the most important results is presented.

4.1. Research Design

The model provides detailed results regarding the long-term development of power plant capacity until 2050 (including the underlying decisions, which take into account the respective national market design), and their impact on electricity wholesale prices, particularly in France. Furthermore, cross-border flows, based on the market coupling results, are examined in order to analyze impacts on the neighboring countries resulting from the investments in the different investigated scenarios. Finally, the effects on greenhouse gas emissions are investigated.

We analyze two (exploratory) main scenarios: the first scenario triggers economically driven model-endogenous investments (Market Scenario) and scenario two assumes politically driven or supported model-exogenous investments in nuclear power plants in France (Policy Scenario). The exogenous nuclear capacity assumption for the Policy Scenario is shown in Table B.17. In addition, two sensitivities of carbon certificate price developments (Low and High, shown in Figure 5) are examined with respect to each scenario in order to evaluate the effects of carbon price developments on the results. Basically, the applied PowerACE model allows investments in nuclear power plants in all markets that have installed capacities so far and have not announced any phase-out plans. In this study, these are Czech Republic, France, Great Britain, and the Netherlands.

4.2. Capacity Development

The increase on the entire RES capacities in all of the modeled countries (from 462 GW in 2020 to 1130 GW in 2050) strongly increases the total power plant capacity across all scenarios. This is illustrated in Figure 6 for the Policy Scenario (Pol) and the Market Scenario (Mkt) for both Low and High sensitivity in 10-year increments from 2020 to 2050.

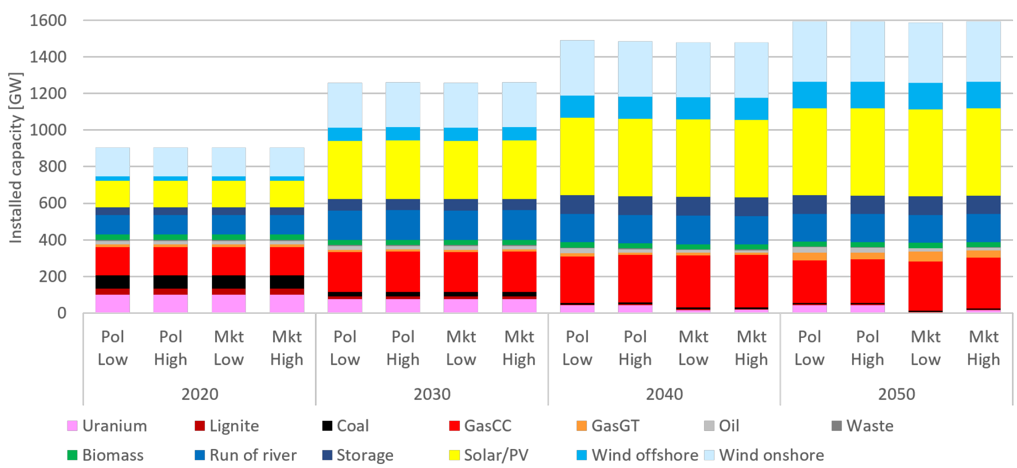

Figure 6: Simulated capacity development by generation type inclusive flexible and RES power plant capacities of all considered market areas and sensitivities.

However, since the RES capacities are exogenous, no model-endogenous changes will be considered (see Appendix B). In order to highlight the differences more clearly, Figure F.13 in the Appendix shows the development of the flexible power plants only.

In the 2030s, many nuclear capacities are decommissioned due to their age (based on the assumed technical lifetime[1]) and thus large differences in the development of the flexible power plants' capacities appear in the developed scenarios. The nuclear capacity in the entire modeled area, thereby, decreases from 101 GW in 2020 to less than 4 GW in 2050 in the Market Low Scenario. Therefore, investments in gas-fired power plants (both combined-cylce gas turbines (CCGT) and open-cycle gas turbines (OCGT)) replace the major part of the decommissioned power plants. The results show a similar level of aggregated total capacity, independently of the scenario.[2]

The power generation capacity in France including RES, shown in Figure 7, increases from about 143 GW in 2020 to 288 GW by 2050. Due to a CRM, the installed flexible capacity increases from the initial level of about 83 GW to almost 91 GW by 2050. In the Policy Scenario, the capacity fluctuations are very small compared to those in the Market Scenario. In particular, around 2040, many nuclear power plants are rapidly decommissioned (due to technical lifetime assumptions). There is, depending on the sensitivity, a capacity gap between the scenarios of up to 10 GW (in 2040). Only in 2050, all scenarios are on par and the difference between the scenarios is less than 80 MW in France caused by the CRM.

The scenarios differ considerably with regard to nuclear power plants in France. The capacity in the Policy Scenario is up to 38 GW higher than in the Market Scenario. 23 nuclear power units of 1.7 GW are added to the market (total 38.5 GW) in the Policy Scenario. The first unit is commissioned in 2033, the last one in 2050. In total, 14 nuclear units are newly installed in the 2030s. However, even at high carbon prices, no additional investments are made in nuclear power plants in the Policy Scenario in France.

In the Market Scenario with the high carbon price development, investments in nuclear reach 8 GW in 2050, while in the Low development, there are no new investments in nuclear power plants in France. Hence, a higher carbon price path provides additional incentives for France to invest in nuclear power plants.[3]

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[1]In our scenarios, technical lifetimes for nuclear power plants are assumed to be 50 years, coal 45 years, gas turbines between 30-50 years, depending on type, and oil between 45-50 years. Values are based on the input data, which is provided in Table 1.

[2]Refinancing of late-stage power plant investments is not always possible during the simulation period.

[3]Overall, only France and the Czech Republic invest in new plant and will have nuclear

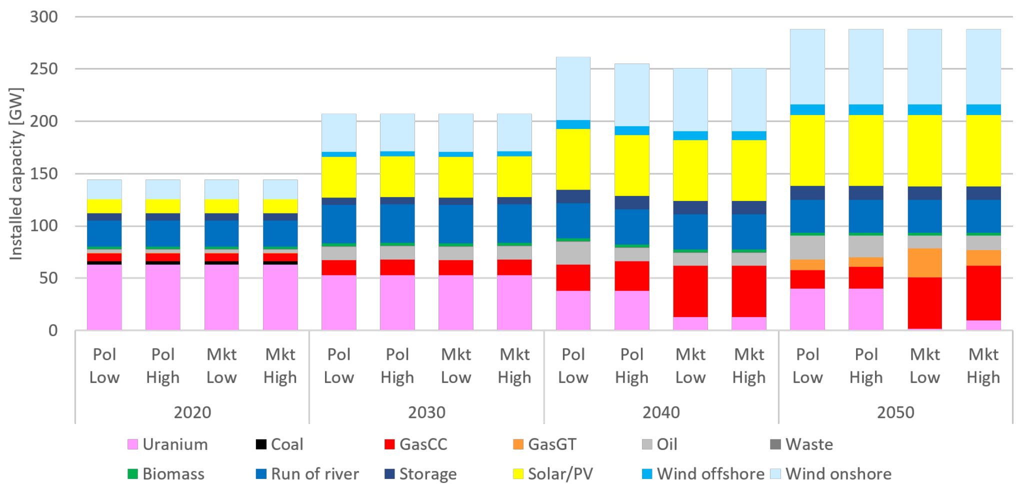

Figure 7: Simulated total capacity development by flexible and RES generation types for all sensitivities in France.

4.3. Price Development

A relevant indicator for evaluating the impact of investments in generation capacity are spot market prices for wholesale electricity for France and its neighboring countries shown in Figure 8 for High sensitivity and in Figure D.11 in the Appendix for Low sensitivity[4]. These prices do not take into account costs for RES, CRMs, or other levies. In particular, RES will need to be dispatched in a different way than in 2022. Basically, the spot market prices increase on average in all considered countries by more than 30 EUR/MWh from 2020's historical values and reach their peak in 2025. Afterwards, the prices continuously decrease until 2050. The price decline is mainly due to the increasing installed RES capacity, which bids on the wholesale market with negative prices. The graph also shows the effect of negative prices on the average price. Negative prices result from an excess of generation over demand in combination with must-run conditions of flexible power plants (e.g., by providing balancing energy). Assuming that the

power plant capacity left by 2050. Hinkley Point C is neglected. No major impact on our studies is expected in the case of neglect due to the small share of nuclear in the total capacity in Great Britain.

[4]Wholesale markets contribute only a part to the refinancing of investments, another part is contributed by CRMs (when introduced).

negative prices are set to zero, this results in a higher average price in each scenario, which is shown as dashed lines in the graph. Thus, prices would be about 22 EUR/MWh higher across all scenarios and sensitivities in 2050.

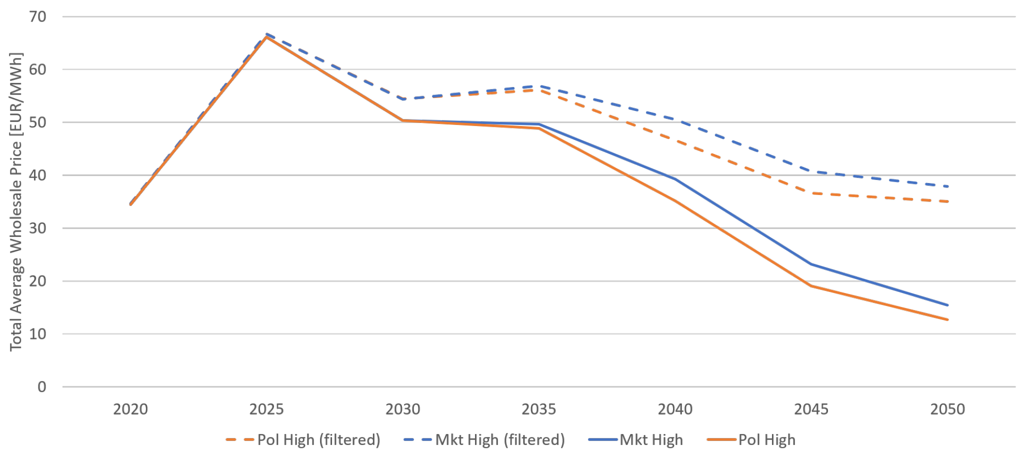

Figure 8: Unweighted annual average wholesale spot market prices for France and the neighboring market areas in the High sensitivity. The lines depict average prices for the scenarios. The dashed lines show the average prices for the different scenarios when the negative prices are filtered out and set to zero. The year 2020 shows historical values based on ENTSO-E (2021). None of the prices take into account levies for Gid, RES, or CRM.

In the box plots, Figure 9 shows that the average wholesale spot market prices for France and the neighboring countries are lower in the sensitivities of the Policy Scenario (the Appendix contains the corresponding graph in Figure D.12 for the Low carbon price path with the similar result). The mean values of the annual spot market prices reveal similar development results across all market areas. Basically, the prices seem to be synchronized in large parts, which is due to the market coupling and the further expansion of trading capacities. Once the exogenous (policy-driven) investments are added to the French market (from 2035), this leads to the lowest average prices in 2050 compared to the respective sensitivities of the Market investment scenario due to the independence of the nuclear power plants from the rising carbon certificate prices. The box plots indicate a clear increase in the variance of prices in the market areas, especially up to 2040. In 2050, the variance decreases again in most market areas. In the comparison between the scenarios, the policy scenario shows a noticeably lower variation, especially in France in 2050. Moreover, the figure shows that the average of the annual spot market prices in France also corresponds to the trend across all neighboring market areas. This might imply that France has a major impact on prices in surrounding market areas and could even have an impact on large parts of Europe.[5]

Figure 10 compares the development of annual spot market prices in France. The average prices for France and neighboring market areas can be found in Appendix D. Over the entire period, the lowest average prices occur in the Policy Low Scenario at the height of 36.39 EUR/MWh on average and thus barely 2.50 EUR/MWh below the price of the Market Low Scenario in the period between 2020-2050. The highest prices can be found in the High Market investment scenario with an average of 40.72 EUR/MWh. Average spot market prices in the Policy Scenario are about 2.50 EUR/MWh (6 %) lower than in the Market Scenario. The differences are highest in the High sensitivities with 2.57 EUR/MWh over the whole period.

It is interesting to note that in 2050, the annual average prices between the two Market sensitivities are almost identical (both 13.56 EUR/MWh). In the Policy scenario, the prices differ by about 2.37 EUR/MWh (6.03 EUR/MWh to 8.41 EUR/MWh) in 2050.

4.4. Cross-border Impacts

The development of the French nuclear installations has an evident impact on the energy systems of the neighbors of France. The summed cross-border flows with France and the neighboring countries can be found in Table 2. Overall, France's trade volume increases. With the exception of Italy, the trade volumes increase by at least 45 % to almost 190 % due to the expansion of transmission lines between markets. France was a net exporter (44.2 TWh) of electricity in 2020 and remains so regardless of the scenario. By 2030, the exchange flows of the sensitivities differ only slightly, but not those of the scenarios.

Despite the fact that France remains a net exporter in all cases and all simulated years, the flow volumes change from 2035 onward: With policy-driven investments, imports of electricity are considerably lower than in the case of market-based investments. In transfer years, i.e., in 2035 and 2040, when age-related decommissionings of nuclear power plant units in France

[5]The assumption of a priority feed-in of RES together with must-run conditions for the reserve supply leads to negative prices.

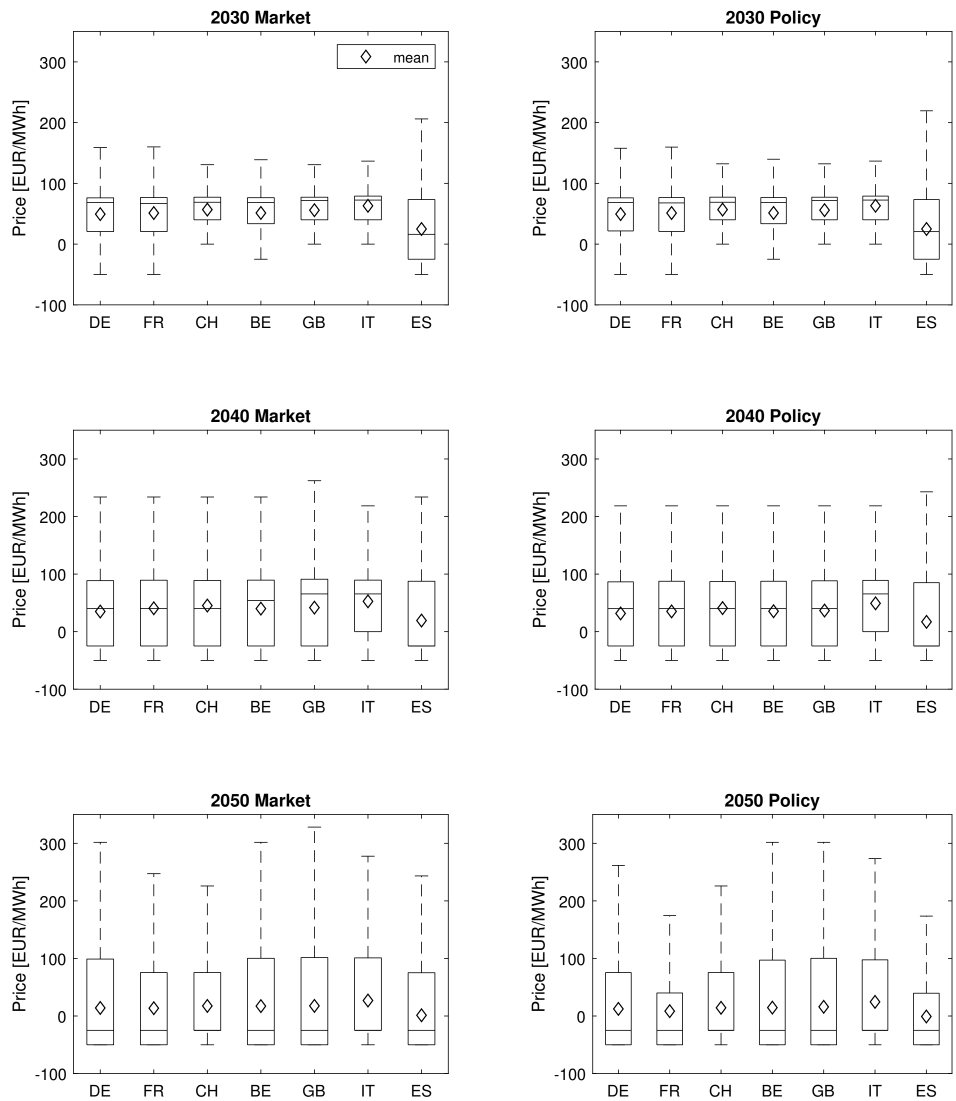

Figure 9: Box plots of wholesale prices between 2030 and 2050 for all market areas surrounding France for the High sensitivity. For a better visualization, the outliers are not shown. The average is indicated as diamond. None of the prices take into account levies for Gid, RES, or CRM.

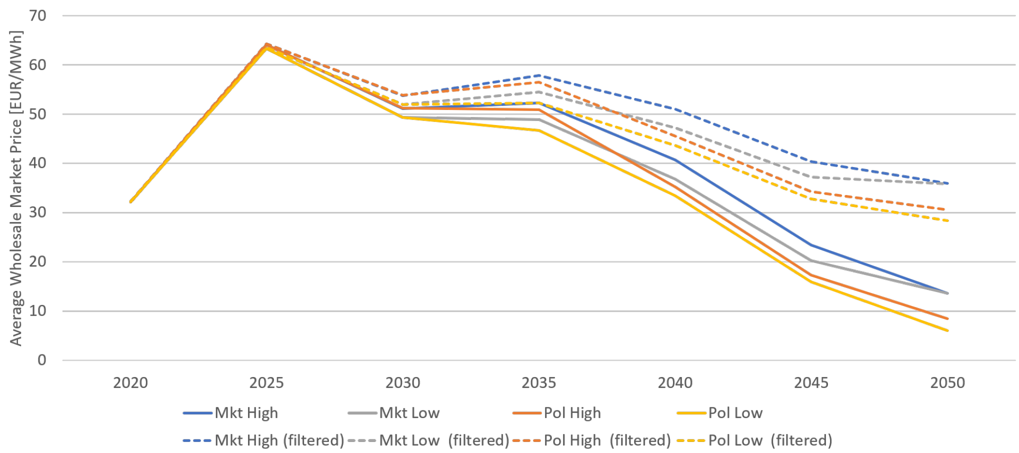

Figure 10: Average wholesale prices between 2020 and 2050 in France for each scenario and sensitivity. The lines depict average prices for the scenarios. The dashed lines show the average prices for the different scenarios when the negative prices are filtered out and set to zero. The year 2020 shows historical values based on ENTSO-E (2021). None of the prices into account levies for Gid, RES, or CRM.

Table 2: Yealy accumulated net export flows of France. Historical value for 2020 according to ENTSO-E (2021), commercial flows.

[TWh]	**High**		**Low**	
	Market	**Policy**	**Market**	**Policy**
2020	44.2	44.2	44.2	44.2
2025	77.7	77.7	78.2	78.3
2030	57.6	57.7	58.4	58.3
2035	6.8	16.7	4.8	13.7
2040	6.8	25.7	5.0	27.1
2045	17.1	34.3	16.5	38.3
2050	29.5	41.7	27.6	42.1

proceed, France imports a large amount of electricity from Germany and Spain (accompanied by the lowest net exports surplus in France), which is clearly visible in 2040.

For the countries to which France is a net exporter, such as Switzerland, these exports are notably higher in the Policy Scenario, especially in the years 2035-2045. Switzerland and Italy thus remain net importers in all cases examined. Italy is highly import-dependent and imports up to 12 times more electricity from neighboring markets than it exports (Table C.21). Italy's self-sufficiency increases due to an expansion of RES, and less electricity needs to be imported into Italy. Belgium supplies France in 2035 in the Market Scenario, but at high carbon prices less, at low carbon prices more. Spain changes from (net) importer of French electricity to massive exporter to France due to a high future RES capacity assumed. Great Britain also reduces its import dependence on France through RES additions. In the medium term, Germany changes from a net exporter to an importer from France. Flow direction changes, however, when the nuclear power plants in France are shut down. Therefore, in the Market Scenario, Germany exports up to 2 TWh per annum more to France than in the Policy Scenario.

Looking at the prices of the neighboring market areas of France, it could be observed that the Policy Scenario leads to a market price reduction on average in Germany of 1.31 EUR/MWh (-3.5 %), in Belgium of 1.71 EUR/MWh (-4.2 %), in Switzerland of 1.76 EUR/MWh (-4 %), in Spain of 1.08 EUR/MWh (-4.5 %), in Great Britain of 1.57 EUR/MWh (-3.6 %), and in Italy of 1.42 EUR/MWh (-2.7 %).

The correlation of the hourly simulated prices of the market areas neighboring France is shown in Table 3 for the Policy Low Scenario. All other scenarios are compiled in Appendix E. Initially, the correlation in 2020 (real historical values) is highest. Afterwards, all scenarios show a decreasing correlation compared to the year 2020 with an interim peak in 2040. Until the year 2050, the correlation drops to the lowest value, i.e., the influence of a single market area decreases. For all directly (adjacent) coupled markets, the correlation increases with the highest value until 2040 (i.e., as long as trading capacities are still being expanded). With regard to France, results show very high correlations (>0.9) with some of the directly neighboring countries. With constant 2040 trade capacities and the increasing RES, the overall correlation decreases slightly.

Table 3: Correlation coefficient between hourly market prices of the neighboring market areas of France in the year shown based on the Policy Low Scenario. 2020 values based on historical day-ahead auction market prices taken from ENTSO-E (2021).

Correlation coefficient		**2020**	**2030**	**2040**	**2050**
CH	FR	0.94	0.91	0.93	0.91
CH	DE	0.85	0.87	0.91	0.85
FR	DE	0.88	0.93	0.89	0.78
CH	IT	0.90	0.85	0.86	0.79
FR	IT	0.87	0.76	0.79	0.76
DE	IT	0.76	0.73	0.75	0.65
FR	ES	0.78	0.53	0.66	0.60
FR	BE	0.94	0.96	0.94	0.91
CH	BE	0.91	0.90	0.92	0.90
CH	ES	0.77	0.48	0.59	0.51
DE	ES	0.63	0.46	0.53	0.33
DE	BE	0.90	0.96	0.93	0.85
ES	BE	0.71	0.49	0.58	0.49
IT	BE	0.83	0.75	0.76	0.70
IT	ES	0.76	0.46	0.56	0.52
GB	FR	0.76	0.90	0.90	0.84
GB	ES	0.58	0.43	0.54	0.42
GB	DE	0.67	0.88	0.88	0.79
GB	CH	0.73	0.82	0.86	0.81
GB	IT	0.70	0.67	0.71	0.62
GB	BE	0.76	0.91	0.95	0.92
Sum		**16.62**	**15.66**	**16.45**	**14.96**

4.5. Carbon Emissions

Table 4 shows the summed changes in carbon emissions for all simulated market areas. It is important to note that the modeling of carbon emissions is exploratory. They do not follow a preset target, but are driven by the applied carbon price path and the corresponding decisions of the market participants. All scenarios are compared to the same value (i.e., the emission level in the respective country in 2020). In all scenarios, carbon emissions of the electricity sector are reduced by more than half by 2050 compared to 2020. With higher carbon prices, the emissions are in sum lower. However, at higher carbon prices, the model cannot invest in additional renewable power plants, but only in flexible power plants or, as the only carbon-neutral investment option, nuclear power plants. Therefore, the differences between the sensitivities are relatively small with regard to carbon emissions. The High carbon price path shows a faster reduction of carbon emissions compared to the Low sensitivity, especially in the early years.

Table 4: Change in cumulated carbon emissions in all simulated market areas compared to 2020's emissions for the different scenarios and sensitivities. Differences are indicated between the scenarios for the same carbon sensitivity.

2020 =1	**Market** **Low**	**Market** **High**	**Policy** **Low**	**Policy** **High**	**Difference** **High** [%]	**Difference** **Low** [%]
2020	1.00	1.00	1.00	1.00	0	0
2025	0.92	0.90	0.92	0.90	0	0
2030	0.63	0.61	0.64	0.61	0	0
2035	0.59	0.58	0.56	0.55	-5	-5
2040	0.53	0.52	0.46	0.45	-14	-13
2045	0.47	0.46	0.39	0.39	-16	-14
2050	0.42	0.39	0.34	0.34	-18	-12

In the Policy Scenario, total emissions in France are between 66 and 67 % lower than in the Market Scenario over the 2020-2050 period (see Table 5). The differences between the sensitivities of the Policy Scenario are very small: In 2050, emissions of both sensitivities are almost equal.

Since only few carbon-neutral power plants are added in the Market Scenario, and old nuclear plants are decommissioned, emissions of the French electricity sector increase 6 times over those of 2020 in this scenario. Even with the more ambitious carbon price paths, emissions increase in the Market Scenario so that in 2050 clear differences between the sensitivities are recognizable at a very high level. The Policy Scenario emits up to 87 % less carbon emissions in 2050 than the Market Scenario in France. In the Policy Scenario, carbon emissions almost double in the years from 2030 to 2035, because RES do not increase rapidly enough[6].

Over the full runtime, emissions in the Market Scenario are most of the time 5 % lower in the High sensitivity than in the Low sensitivity in France. However, in 2050, the difference is substantial, with emissions being 22 % lower in the High sensitivity.

Table 5: Change in cumulated carbon emissions in France compared to 2020's emissions for the different scenarios and sensitivities. Differences are indicated between the scenarios for the same carbon sensitivity.

2020 =1	**Market** Low	**Market** High	**Policy** Low	**Policy** High	**Difference Low** [%]	**Difference High** [%]
2020	1,00	1,00	1,00	1,00	0	0
2025	1,11	1,10	1,11	1,09	0	-1
2030	1,10	1,05	1,09	1,05	-1	0
2035	3,62	3,74	1,80	1,92	-50	-49
2040	6,01	6,12	1,27	1,26	-79	-79
2045	5,83	5,84	1,02	0,91	-83	-84
2050	5,81	4,53	0,77	0,78	-87	-83

5. Discussion and Limitations

In the following sections, we intensively discuss the two research questions and the limitations of the study.

5.1. Required Investments in Nuclear Power Plants in France

In France, the structure of the power plant fleet changes substantially between the scenarios considered. In the Policy case, permanently high nuclear

[6]It is important to note that only the country-dependent production-based carbon emissions are considered here, not the consumption-based ones. When importing carbon-free electricity, consumption-based emissions could become much less.

capacities are installed, while in the Market case, nuclear capacities decrease sharply in the years after 2030. Within 10 years, more than half of the installed capacity would be decommissioned without investing in an additional nuclear power plant during that time. Only at the end of the simulation period, a few investments in nuclear power plants occur in the Market Scenario and the High sensitivity case. Therefore, a stable capacity level of nuclear power plants seems to be possible only via government investment incentives in France[7].

A higher carbon price path stimulates more nuclear investments. However, this does not apply to both scenarios. While in the Policy Scenario, there are no differences between the carbon price paths with regard to investments in nuclear power plants (43.6 GW in 2050), clear differences are visible in the Market Scenario: In the High sensitivity, up to 14.8 GW of nuclear power plants will be installed in 2050 in the countries investigated, while in the Low sensitivity only about a quarter (3.6 GW) will be installed.

Throughout all scenarios, the resulting generation gaps are generally compensated for by substantial gas investments. Also Maïzi and Assoumou (2014) show that investments are mainly made in fossil-fired power plants without the specification of a carbon reduction target, but only applying rising carbon prices.

Our results show that the higher the carbon price path is assumed, the lower the total investment in gas-fired power plants in 2050, which confirms a control effect via the carbon price. However, a carbon price in 2050 of 150 EUR/t_{CO_2} does not seem to be sufficient to decarbonize the electricity system totally. This contrasts with the findings by Shirizadeh and Quirion (2021), which consider different carbon price scenarios and claim that at 100 EUR/t_{CO_2} the energy sector would become nearly carbon-neutral. They also observe that the availability of new nuclear power plants would be far less important to achieve carbon neutrality, which could not be shown in our study for France. However, we have not endogenously considered RES and storage expansion. Despite this, our results are in line with Shirizadeh and Quirion (2021) who state that government support for investment in new nuclear power plants is probably unavoidable, as the competitiveness of nuclear power in the liberalized market is questionable, and is consistent

[7]Under the assumed conditions, the market will clearly miss the nuclear capacity targets shown in French Government (2017)

with Kan et al. (2020), who reached a similar conclusion for Sweden.

Overall, it can be stated that the answer to RQ1 "Can the current market design in France trigger the required investments in nuclear power plants or is additional support necessary?" on the basis of the results presented allows only one fairly clear conclusion. Figure 7 shows the clear differences between the investment scenarios in terms of investments in nuclear capacities. For example, in the Market Scenario, considerably less nuclear power plant capacity is invested in, even at high carbon prices. Thus, under the assumptions made, it is very doubtful whether, without additional government intervention, the goal of generating 50 % of electricity in France (according to French Government, 2018) from nuclear power plants in 2035 and following could be achieved (assuming there is no lifetime extension of nuclear power plants). These doubts are confirmed by Wealer et al. (2021a). Even in the policy-driven scenario, the installed nuclear capacities are not sufficient to close the remaining quantities. Additional gas-fired power plants are necessary to cover the complete demand in France, especially during peak load hours. In 2050, in the Policy Scenario, RES, storage, and nuclear power plants are not sufficient to cover demands, but a peaker generation technology (oil- or gas-fired turbines) is necessary.

The investigation does not intend to answer how the state support for nuclear power plants could be designed. Support based on CRMs is possible and already considered in line with the version that has already been introduced in France. However, we could not find any indication that proves that the introduced CRMs are sufficient to incentivize nuclear investments rather than investments in other generation technologies. Additional investment support may indeed be necessary (e.g., low-interest credits, purchase or price guarantees, investment subsidies, tax benefits, levy financing, etc.).

With regard to carbon emissions, there are major differences between the scenarios. As soon as new nuclear capacity is added, carbon emissions decrease considerably in the Policy Scenario compared to the Market Scenario. Up to 18 % less carbon is emitted throughout all simulated market areas in the Policy Scenario due to the generation of the nuclear power plant fleet in 2050. Maïzi and Assoumou (2014) obtain similar findings.

On the contrary, in the Market Scenario, almost completely gas-fired power plants are added. The carbon emissions of the power sector strongly increase in France in all of the investigated scenarios as RES are not yet sufficient to cover large parts of the electricity generation. In 2040, they are over 6 times higher than in 2020, even in the High carbon price sensitivity.

Even in the Policy Scenario, carbon emissions almost double between 2030 and 2035, which is why an extension of the lifetime of some power plants could be considered temporarily until the RES share is high enough. The results confirm the findings by Kunsch and Friesewinkel (2014), who found for Belgium that a rapid phase-out of nuclear generation primarily benefits fossil fuels and leads to undesirable disadvantages in terms of carbon emissions. Therefore, in France, the carbon neutrality target in the electricity sector will not be met, regardless of the investigated scenarios. Thus, for fossil power plants, such as gas-fueled ones, either the resulting carbon emissions need to be captured (e.g., by carbon capture and storage) or the used fossil fuel needs to be substituted by a sustainable fuel.

5.2. Cross-border Effects Due to State-Driven Investments in France

The second research question focuses on the cross-border effects in strongly coupled electricity markets. Overall, in all considered countries, spot market prices decrease. High nuclear capacities (i.e., Policy Scenario) have a lowering effect on the electricity prices of neighboring market areas, so that on average, the prices are by more than 1 EUR/MWh (about 2 %) reduced. Therefore, cross-border effects are observed in neighboring market areas. At high carbon prices, nuclear power plants have an additional price dampening effect, with the exception of Germany.

The high RES generation in Spain leads to negative average spot market prices if sufficient flexibilities are not available. In the case of negative or low prices, which occur due to must-run conditions, i.e., balancing energy provision, it can be expected that investors install additional flexibility (on both the producer and consumer side, e.g., storage, demand in the form of electrolyzers or additional trading capacities to neigboring countries) that can presumably avoid negative prices to a greater extent in the market areas. However, flexibility expansion has been neglected or is exogenously given in our study.

The price effects have also an impact on the cross-border flows, since electricity flows usually from the lower-priced to the higher-priced market area until the trading capacity is saturated or the price between the market areas is balanced (e.g., Zimmermann et al., 2021). The trading capacity that allows exchanges between countries is assumed to increase over time (see Tables B.18, B.19, and B.20). Therefore, flows across market borders and, consequently, the total electricity exchange volume as well as the net export/import of France with neighboring countries increase, in some cases, to almost double the value compared to 2020. Overall, France is and remains a net exporter of electricity. However, in the Market investment scenario, substantially more electricity is imported to France than in the Policy Scenario (see Table 2). Therefore, the net export volume decreases from more than 57 TWh in 2030 to less than 14 TWh in the Policy Low Scenario and to less than 5 TWh in the Market Low Scenario in 2035. Reasons are that neighboring countries with high RES capacity can be self-supplying to a higher degree (i.e., Italy) or even become net exporters of electricity to France (i.e., Spain).

Due to higher exchanges between market areas, cross-border effects (i.e., prices, cross-border flows) increase, particularly between direct (neighboring) coupled markets. However, the effects of the scenarios on the correlation can be well analyzed between the years 2040 and 2050, since there is no expansion of trading capacity, only an expansion of RES and flexible power plants. Overall, the correlation between all countries decreases between these years independent of the scenario. Therefore, effects originating from a single market area on other markets seem to decrease (shown in Table 3 and in Appendix E). The effect may vary due to different levels of RES addition. The dominant RES technology in a market area may play a role: For example, in Spain, solar PV generation is considerably higher compared to Germany or the UK, where wind generation is increasing strongly. In both cases, correlation between these countries shrinks. The offset of the solar feed-in peak, which occurs due to different sunrises and sunsets in the market areas, can further affect correlations due to high shares of solar/PV in 2050.

Additionally, the carbon price and the continued reliance on fossil fuels, along with high trading capacities, lead to high correlations of prices particularly between directly coupled areas. Due to higher nuclear generation in France in the Policy Scenario, directly coupled markets also show a higher sum of correlations across all years than in the Market Scenario.

5.3. Limitations

Despite the careful modeling, our work has some important limitations that should be briefly mentioned here. For analyses that are conducted in the future, and especially for studies that extend to the year 2050, some assumptions are required that are subject to uncertainties, but are essential for such a scenario analysis. Therefore, a commonly accepted scenario framework of the European Transmission System Operators (ENTSO-E, 2020) was used as the main input source for this study, and partly, own assumptions were made.

The own assumptions were, as far as possible, supported with historical data, such as ENTSO-E (2021) or Eurostat (2020), in order to derive estimations for the future (i.e., RES feed-in or demand time series). Some data are not available for each year until the end of the simulation, so necessary values are inter- or extrapolated.

Since there is no model-derived RES addition in our approach, no adjustments of RES capacity due to scarcity prices on the spot market could be carried out. We also consider only one weather year. Furthermore, the assumed technologies of RES or flexible power plants are subject to a development that can only be predicted to a limited extent. Future work could address a model-endogenous expansion of RES, which might change the share of RES in production and, therefore, carbon emissions. However, in terms of the necessary highly flexible capacity and the need for renewal of nuclear investments in France, this might play a minor role and rather reduce investment incentives due to the merit-order effect.

The inner-country electricity grid was neglected, except for the interconnection capacities between market areas based on the assumption of ENTSO-E (2020), which implicitly considers a domestic grid expansion.

The assumed construction of gas-fired power plants remains questionable against the background of the decarbonization of the entire electricity system. For carbon neutrality, CO_2 would have to be captured. However, particularly new gas power plants would be able to combust hydrogen or use synthetic gases, which makes power plants carbon-free in the case of the use of green hydrogen.

Another important role is hydropower, which could not be considered in detail due to the underlying complexity (i.e., cascade structures). In some market areas, hydro reservoir power plants have been considered static based on historical production. This approach is sufficient for the scope of this study, as the contribution of reservoirs on the investment decisions examined is rather small for most of the analyzed market areas. Therefore, hydro reservoirs are modeled only for Switzerland with larger details, where the contribution to domestic generation adequacy is the highest. Therefore, the key findings of the results of this paper are not negatively affected by this.

Regarding the geographical resolution, all neighboring market areas of France were modeled, which is the main subject of this study. However, since not all countries connected to the ENTSO-E transmission grid have been modeled, some smaller effects caused by other countries cannot fully be accounted for in the results.

6. Conclusion and Policy Implications

This exploratory study shows whether investments in nuclear power plants are incentivized by the market (this includes both revenues on the spot market and on the CRM) or investments are only made with political support and assessed against the background of the government's carbon-neutral targets. Based on the results of the study, implications for political action can be derived.

In 2017, the French government set energy policy targets to achieve carbon neutrality in 2050. The French government expressed concrete plans for a nuclear power plant investment program using public financing to build at least six new nuclear power plants. (Wakim, 2019; Reuters, 2019, 2022).

From a systemic perspective, such program sounds favorable. Our results show that, without government support, the necessary amount of generation capacity to cover demand seems to be installed (mainly driven by the CRM), but decarbonization targets would be difficult to achieve if substantial nuclear capacity was decommissioned due to aging (see Figure 1). At some point, emissions for the electricity sector in France would heavily increase when nuclear power plants were fully replaced by gas-fired power plants using preferably fossil fuels. In the scenario with market-based investments, an increase in emissions in France's electricity sector occurs to the greatest extent with up to 87 % (in 2050) compared to a policy-driven scenario or even up to six times more emissions compared to 2020 levels. Consequently, mainly gas-fueled power plants are likely to benefit from the Market Scenario.

However, even in the scenario with policy-driven nuclear investments emissions would increase to almost double the 2020 level in the mid-term. Such a temporary increase could be prevented if more nuclear power plants will be supported by the French government or gas-fired power plants can be fully fired with green (carbon neutral/free) gases, especially from 2030 onwards (which would even lead to complete decarbonization in the end), but both can be doubted at such an early stage.

The scenario with market-based investment decisions shows that sheer private economic decisions do not support any substantial investments in nuclear power plants. Only with high carbon certificate prices, as assumed towards 2050, a few market-driven investments in nuclear capacities are carried out. But the results show further that even the nuclear investments in the Policy Scenario do not seem to be sufficient to achieve full decarbonization, since other technologies are still needed (as, e.g., peaking plants) to fully meet the demand in France. In this scenario, emissions in France would fall to around three quarters and in all considered market areas to more than one third in 2050 of the 2020 value. However, these results do not consider a possible fueling of gas power plants with green gases. In summary, the current market design does not help to incentivize sufficient nuclear capacity, and additional support (e.g., from the government) would be necessary in France, otherwise carbon neutrality is difficult to achieve.

Nevertheless, cross-border effects were observed to occur in all scenarios to various extents: In a policy-driven investment scenario, average spot market prices are lower in France and neighboring countries compared to a market-driven investment scenario. The larger capacity of nuclear power plants thus has a dampening effect on electricity prices and the neighboring countries also benefit from this. In all of the market areas investigated, spot market prices develop very similarly due to market coupling. All scenarios and sensitivities continue to show the strong dependence of spot market prices for electricity on the carbon price in all market areas. As a result of the increase in trading capacities caused by the expansion of interconnection lines, cross-border effects originate from a single market area decrease even though the total effect might be growing.

The total exchange volumes between France and its neighbors will almost double during the simulation period and France will remain a net exporter in all scenarios. However, in particular in the market-driven investment scenario, France's electricity export surplus will decrease considerably once a large amount of nuclear capacity is removed from the market. Regarding neighboring countries, Spain will become a large net exporter to France in the future due to its high installed RES capacity. At the same time, Italy will be less dependent on imports from France.

In terms of policy measure improvements, the adopted scenario from ENTSO-E (2020) seems far from sufficient to achieve the carbon targets. Therefore, further investments should be made in carbon-neutral power plants, e.g., nuclear, geothermal, biomass, etc., as these can be options to achieve the goal. In order to replace the requested amount of nuclear power plant capacity, this means that the French government will have to launch a public support program. In addition to the scenarios assumed in this paper, however, further investments in nuclear power plants, substantial lifetime extensions of existing power plants (i.e., >50 years, which is considered by the French government (Reuters, 2022)), or decarbonization measures are needed to achieve the (EU and French) target of net zero emissions in 2050.

But power plant investments should also be accompanied by other measures. For example, further expansion of RES and storage capacity, demand flexibility, conversion of oil and gas turbines and the underlying infrastructure to carbon neutral fuels, or carbon capture and storage can be further (additional) measures to achieve carbon neutrality.

Further increasing carbon certificate prices could also contribute to some extent to the reduction of carbon emissions, as shown in Section 4.5. However, the results show that the share of RES seems to have a higher influence on the carbon reduction than the final price of the carbon certificates (A higher carbon price might in turn incentivize more RES, which is not investigated in this study.).

Another measure might be the expansion of transmission grids and interconnection capacities, which ensures higher trading capacities between market areas. Furthermore, as the trading capacity increases, spots market prices converge more, but the interdependence of markets decreases from 2040 to 2050 due to increased RES expansion while the trading capacity remains equal. An intensive exchange of electricity between markets, particularly in scarcity situations, can also have a positive impact on generation adequacy and can stabilize or even increase the level.

Finally, this study provides an up-to-date overview of impacts of incentives-based investments in new power plant capacity, especially in nuclear power, in western Europe in the current political framework. However, the study does not claim to be a comprehensive work of the topic. Following on from this paper, investigations could address generation adequacy, corresponding levels of required investment incentives, and other investment support. In particular, the question of additional support could be investigated in combination with the state-driven investment scenario. In addition, storage and demand flexibility (by using, e.g., electrolyzers for the production of green hydrogen and fuels or e-mobility) are other important flexibilities in order to lower peak demand, which would be beneficial to analyze.

In order to switch to green fuels, a regulatory phase-out pathway of fossil methane may be an option, for example, with an increasing addition of green hydrogen, e-methane, or bio-methane in the gas system.

For the identification of more comprehensive political measures, the modeling framework could be extended to the Scandinavian countries, in order to be able to consider the geographical conditions regarding (pumped) storage (potentials) and hydrogen production there. Generally, the full integration of hydrogen, both supply and demand side, and other flexibility options could provide additional insights. Despite the improvements and limitations highlighted in some places in this paper, this paper provides many useful findings and contributes to an increase in insights.

Credit author statement

Florian Zimmermann: Term, Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration; **Dogan Keles:** Funding acquisition, Conceptualization, Methodology, Investigation, Validation, Writing - Review & Editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Modeling Capacity Remuneration Mechanisms

Decentralized obligation implementation

In RTE (2017), the design of the French capacity market has been fully described. Following RTE (2017), the implementation in Zimmermann et al. (2017) and Kraft (2017) was developed for the agent-based electricity market simulation model: The reference capacity is determined based on the future annual maximum demand plus a security factor (in this study, the security factor was set negative based on the assumption that, e.g., generation capacity from abroad contributes to meeting peak demand). Each utility and large consumer (obligated parties) must acquire capacity obligations in an amount equal to its own share of peak demand.

The generation entities offer the capacity obligations to the obligated parties in the amount of their own capacity that can be generated at the time of peak demand. The underlying price of the capacity obligations takes into account the annual difference between the expected revenues on the spot market and the gap to cover all costs of the power plant. Then, a market price and the corresponding quantity are determined by an auction. The power plant dispatch is, furthermore, carried out via spot market clearing.

Central buyer implementation

The central form of capacity market was developed in Keles et al. (2016) for the agent-based electricity market simulation model and is based on the Forward Capacity Market of ISO New England (2014). This mechanism was assumed to be the most proximate CRM for Italy, Poland, and Great Britain (Bublitz et al., 2019), as well as in Belgium from 2025 onward (Elia Group, 2021).

The regulator determines the capacity requirements for flexible, mostly conventional, power plants four years in advance. The basis for this is the forecast peak load including a safety margin minus capacity credits for RES in the respective auction year. The market outcome is determined based on a demand curve as described by Cramton and Stoft (2005). All generating units receive the market price as a capacity payment. The power plant dispatch is carried out via spot market clearing furthermore.

Strategic reserve implementation

A central authority (i.e., transmission system operator or regulator) contracts the required capacity for a SR annually via an auction, as implemented in the agent-based electricity market simulation model (Bublitz et al., 2015). Power plants that undercut a required cold start time are eligible to participate and offer their capacity at a price based on their annual fixed and opportunity costs. In addition, a no-way-back rule was assumed, which precludes a return to the spot market. In the end, the power plants are allocated at minimum cost in the SR. The power plants are only dispatched if the spot market does not yield a market result due to a supply shortage at the maximum price, starting with the power plant with the lowest variable costs. The SR was assumed for Germany over the entire simulation period and in Belgium until 2024.

Appendix B. Input Data

Table B.6: Annual production volumes in TWh of the RES type wind onshore for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [TWh]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	4.84	5.23	6.57	6.03	11.35	14.41	35.10	55.79
BE	3.73	3.79	4.44	4.72	8.26	11.45	17.01	22.57
CH	0.11	0.11	0.13	0.12	0.34	0.52	4.21	7.89
CZ	0.57	0.50	0.59	0.61	1.00	2.17	3.54	4.91
DE	74.69	73.21	95.41	98.00	137.04	170.37	251.73	333.09
DK	10.59	9.68	11.38	10.04	10.90	11.48	16.62	21.77
ES	49.25	48.83	49.01	50.74	86.03	120.94	165.88	210.83
FR	20.81	20.81	23.81	27.50	53.62	87.50	180.76	274.02
GB	21.42	20.63	26.34	30.00	3.14	31.11	49.09	67.06
IT	14.84	17.69	17.74	17.72	24.33	51.70	64.80	77.89
NL	5.70	5.62	7.40	7.49	3.03	19.14	28.13	37.13
PL	10.86	12.59	14.91	12.80	13.66	15.02	21.26	27.50
PT	11.60	12.47	12.25	12.62	7.52	29.15	39.76	50.38

Table B.7: Annual production volumes in TWh of the RES type wind offshore for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [TWh]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
BE	1.81	1.63	2.03	2.70	8.06	13.56	25.52	37.17
DE	5.94	6.71	10.28	11.95	40.68	65.95	152.02	226.26
DK	3.54	3.10	3.40	3.86	10.04	17.73	35.52	52.50
FR	0.00	0.00	0.00	0.00	9.84	18.82	33.32	48.97
GB	11.84	10.08	14.61	18.18	54.54	89.27	145.32	205.85
IT	0.00	0.00	0.00	0.00	0.00	0.00	2.74	4.56
NL	0.67	1.63	2.18	2.09	19.28	33.09	65.93	97.02
PL	0.00	0.00	0.00	0.00	0.00	16.26	40.54	67.57
PT	0.00	0.00	0.00	0.00	0.33	0.58	1.54	2.35

Table B.8: Annual production volumes in TWh of the RES type run of river for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [TWh]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	37.03	39.23	38.50	37.62	33.84	37.81	42.72	45.18
BE	0.79	0.83	0.78	0.74	0.31	1.01	1.22	1.33
CH	16.60	16.57	15.95	16.91	15.42	16.17	18.17	19.17
CZ	1.83	1.90	1.78	1.60	1.17	1.58	2.11	2.37
DE	20.09	21.07	21.09	19.53	16.83	30.59	32.49	33.44
DK	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
ES	27.89	35.58	18.76	32.69	26.81	36.98	44.33	48.01
FR	55.49	60.22	50.52	64.74	58.55	59.12	63.70	65.99
GB	5.38	4.86	4.96	4.45	3.40	7.28	8.27	8.77
IT	44.37	41.82	35.93	47.89	35.89	42.25	46.84	49.14
NL	0.09	0.10	0.06	0.07	0.13	0.12	0.10	0.10
PL	2.05	2.21	2.56	2.01	1.24	2.03	2.79	3.17
PT	8.97	15.48	6.98	12.47	14.17	17.01	20.42	22.12

Table B.9: Annual production volumes in TWh of the RES type biomass for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [TWh]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	4.35	4.45	4.61	4.59	3.43	3.37	3.36	3.35
BE	4.51	4.46	4.75	4.43	5.55	0.85	0.81	0.78
CH	0.48	0.54	0.65	0.63	3.68	4.86	4.86	4.86
CZ	4.70	4.66	4.85	4.73	4.99	5.91	5.91	5.91
DE	44.13	44.51	44.52	44.24	45.28	36.80	26.41	16.02
DK	3.26	3.98	5.38	5.04	10.24	3.92	3.47	3.02
ES	5.00	4.95	5.31	5.14	6.99	9.18	8.09	7.01
FR	4.52	5.41	5.56	6.13	10.50	10.55	10.25	9.94
GB	25.89	25.91	26.58	29.23	55.40	31.21	29.28	27.35
IT	12.16	12.38	12.53	12.49	21.22	21.22	21.22	21.22
NL	2.94	2.90	2.70	2.38	26.24	1.80	1.59	1.38
PL	9.93	7.94	6.40	6.46	20.14	6.10	9.58	13.07
PT	2.81	2.77	2.86	2.83	5.06	5.06	5.06	5.06

Table B.10: Annual production volumes in TWh of the RES type solar/ PV for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [TWh]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	0.94	1.10	1.27	1.44	5.83	12.02	25.60	38.77
BE	0.00	0.00	0.00	0.00	7.20	9.92	13.30	17.38
CH	1.12	1.33	1.68	1.94	3.93	5.41	7.47	9.83
CZ	2.26	2.13	2.19	2.36	3.15	5.14	5.48	7.04
DE	38.73	38.10	39.40	45.78	71.84	88.58	92.21	105.79
DK	0.00	0.00	0.00	0.00	1.45	2.37	5.59	8.35
ES	13.83	13.61	14.36	12.71	43.05	79.64	103.22	143.33
FR	3.80	4.45	5.05	5.76	28.12	45.86	68.19	94.90
GB	1.40	2.04	2.98	3.65	15.98	17.74	27.41	35.03
IT	22.94	22.10	24.38	22.65	35.06	66.12	78.38	107.25
NL	0.01	0.05	0.09	0.30	8.96	17.32	18.59	25.01
PL	0.00	0.00	0.00	0.00	3.03	8.67	17.38	26.95
PT	0.46	0.48	0.52	0.51	6.94	8.20	23.36	34.30

Table B.11: Annual capacity development in GW of solar/ PV for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [GW]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	0.94	1.10	1.27	1.44	5.00	12.01	22.00	27.00
BE	3.13	3.33	3.62	3.99	7.59	10.45	14.30	16.22
CH	1.39	1.66	1.90	2.17	4.00	5.50	7.60	8.65
CZ	2.08	2.07	2.07	2.08	3.00	4.90	5.23	5.40
DE	39.22	40.68	42.29	45.18	73.30	91.30	97.40	100.45
DK	0.78	0.85	0.91	1.00	1.40	2.30	5.70	7.40
ES	4.70	4.71	4.72	4.76	22.78	43.43	65.05	75.86
FR	7.14	7.70	8.61	9.62	23.87	38.96	58.38	68.09
GB	9.60	11.93	12.78	13.12	15.01	17.12	26.90	31.79
IT	18.90	19.28	19.68	20.11	26.48	50.88	61.05	66.13
NL	1.52	2.05	2.90	4.52	10.90	25.00	25.00	25.00
PL	0.11	0.19	0.29	0.56	3.50	8.17	20.16	26.15
PT	0.45	0.51	0.58	0.67	3.71	9.14	14.88	17.74

Table B.12: Annual capacity development in GW of wind onshore for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [GW]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	2.49	2.73	2.89	3.13	5.50	9.00	13.00	15.00
BE	1.46	1.66	1.92	2.08	3.43	4.28	5.41	5.98
CH	0.06	0.08	0.08	0.08	0.18	0.26	1.85	2.65
CZ	0.28	0.28	0.31	0.32	0.50	0.96	1.30	1.47
DE	41.30	45.28	50.17	52.45	70.50	81.50	90.80	95.45
DK	3.81	3.98	4.23	4.42	5.00	5.00	5.00	5.00
ES	22.94	22.99	23.12	23.41	38.96	48.58	53.51	55.97
FR	10.30	11.57	13.50	14.90	26.54	36.06	60.01	71.99
GB	9.21	10.83	12.60	13.55	15.11	17.50	18.26	18.64
IT	9.14	9.38	9.74	10.23	12.12	17.52	22.14	24.45
NL	3.03	3.30	3.25	3.44	5.70	7.80	9.38	10.17
PL	4.89	5.75	5.76	5.77	7.00	7.24	7.70	7.93
PT	4.94	5.12	5.12	5.17	5.61	8.90	12.93	14.94

Table B.13: Annual capacity development in GW of wind offshore for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [GW]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
BE	0.71	0.71	0.88	1.19	2.27	4.27	6.07	6.97
DE	3.28	4.15	5.41	6.40	10.80	17.05	35.55	44.80
DK	1.27	1.27	1.26	1.70	2.60	4.80	8.00	9.60
FR	0.00	0.00	0.00	0.00	2.92	4.92	8.36	10.09
GB	5.09	5.29	6.99	8.22	17.64	25.10	35.47	40.65
IT	0.00	0.00	0.00	0.00	0.00	0.60	0.60	0.60
NL	0.36	0.96	0.96	0.96	5.20	11.30	16.15	18.58
PL	0.00	0.00	0.00	0.00	0.00	3.60	10.32	13.68
PT	0.00	0.00	0.00	0.00	0.10	0.26	0.53	0.66

Table B.14: Annual capacity development in GW of run of river for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [GW]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	13.65	14.12	14.15	14.52	12.75	21.51	18.05	16.31
BE	1.42	1.43	1.42	1.42	0.80	0.81	0.81	0.81
CH	4.77	4.81	4.84	4.87	5.06	7.81	7.81	7.81
CZ	2.26	2.26	2.27	2.26	1.31	1.49	1.49	1.49
DE	11.26	11.21	11.12	10.94	10.09	11.03	11.03	11.03
DK	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
ES	20.05	20.08	20.08	20.08	13.88	36.95	36.95	36.95
FR	25.55	25.62	25.71	25.79	23.69	36.66	33.38	31.75
GB	4.68	4.74	4.77	4.78	3.16	3.88	3.88	3.88
IT	22.22	22.30	22.43	22.50	15.97	28.13	28.13	28.13
NL	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05
PL	2.37	2.39	2.39	2.39	1.38	1.40	1.40	1.40
PT	6.17	6.96	7.23	7.24	7.62	12.47	12.47	12.47

Table B.15: Annual capacity development in GW of biomass for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [GW]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
AT	1.13	1.12	1.02	1.00	0.61	0.60	0.60	0.60
BE	0.77	0.75	0.74	0.72	0.89	0.21	0.21	0.21
CH	0.03	0.03	0.04	0.04	0.91	1.20	1.20	1.20
CZ	0.75	0.75	0.77	0.75	0.91	1.06	1.06	1.06
DE	7.24	7.45	7.75	8.36	7.94	6.64	5.24	4.54
DK	1.08	1.14	1.61	1.62	2.86	0.67	0.63	0.61
ES	0.90	0.90	0.90	0.91	1.59	2.23	2.23	2.23
FR	0.91	1.02	1.06	1.27	2.55	2.57	2.57	2.57
GB	4.34	4.73	4.91	6.37	8.38	4.89	5.14	5.27
IT	1.95	2.04	2.06	2.11	4.80	4.93	4.93	4.93
NL	0.46	0.44	0.45	0.45	4.54	0.54	0.54	0.54
PL	0.95	0.95	0.94	0.96	3.50	1.41	2.33	2.79
PT	0.54	0.55	0.54	0.61	1.01	1.11	1.21	1.27

Table B.16: Annual demand volumes in TWh for the different market areas based on Eurostat (2020) until 2018 and ENTSO-E (2020) National Trends Scenario.

Market Area [TWh]	**2015**	**2016**	**2017**	**2018**	**2025**	**2030**	**2040**	**2050**
Austria	61.18	62.04	62.89	63.07	76.89	78.84	90.94	103.05
Belgium	81.67	82.24	82.28	82.76	87.35	91.28	104.97	118.67
Switzerland	58.25	58.24	58.48	57.65	62.45	60.97	56.64	52.31
Czech Republic	54.48	55.85	57.38	58.00	72.72	77.85	87.14	96.43
Germany	514.95	517.55	518.95	512.93	541.60	550.67	625.10	699.52
Denmark	30.81	31.09	31.29	31.08	52.16	45.82	57.16	68.51
Spain	232.04	232.51	239.10	238.46	259.73	276.95	323.83	370.71
France	438.19	445.98	442.70	440.29	496.44	485.86	504.87	523.88
Great Britain	303.59	304.14	299.68	299.76	312.06	317.46	347.81	378.15
Italy	287.48	286.03	291.97	293.08	327.91	324.44	322.18	319.91
Netherlands	103.83	105.46	106.52	107.97	113.73	118.81	130.15	141.50
Poland	127.82	132.84	135.79	140.47	180.72	182.21	206.14	230.06
Portugal	45.81	46.39	46.64	47.96	52.46	57.70	69.70	81.70

Table B.17: Development of nuclear capacity in France in different scenarios in GW.

Nuclear capacity scenario [GW]	**2030**	**2040**	**2050**	**Source**
Policy Scenarios (our assumption)	53.0	38.0	40.0	Aligned with French Government (2018) target of being able to cover about 50% of generation by nuclear power plants.
National Trends	58.2	43.1	N/A	ENTSO-E (2020)
Distributed Energy	58.2	49.0	N/A	ENTSO-E (2020)
Global Ambition	56.6	37.2	N/A	ENTSO-E (2020)
Futurs énergétiques 2050 M0			0.0	RTE (2021)
Futurs énergétiques 2050 M1 and M23			16.0	RTE (2021)
Futurs énergétiques 2050 N1			29.0	RTE (2021)
Futurs énergétiques 2050 N2			39.0	RTE (2021)
Futurs énergétiques 2050 N03			51.0	RTE (2021)

Table B.18: Trading capacity between the market areas in GW for the year 2020. Values based on ENTSO-E (2020, 2018); German TSOs (2019) and historical values based on the yearly average of the day-ahead NTCs from ENTSO-E (2021).

From \ To	**AT**	**BE**	**CH**	**CZ**	**DE**	**DK**	**ES**	**FR**	**GB**	**IT**	**NL**	**PL**
AT	-	-	1200	900	7500	-	-	-	-	405	-	-
BE	-	-	-	-	1000	-	-	1800	1000	-	2400	-
CH	1200	-	-	-	4600	-	-	1300	-	4240	-	-
CZ	800	-	-	-	2100	-	-	-	-	-	-	600
DE	7500	1000	2700	1500	-	1472	-	2300	0	-	4250	500
DK	-	-	-	-	1054	-	-	-	1400	-	0	1200
ES	-	-	-	-	-	-	-	2600	-	-	-	-
FR	-	3300	3150	-	1800	-	2800	-	2000	4350	-	-
GB	-	1000	-	-	0	1400	-	2000	-	-	1000	-
IT	235	-	1910	-	-	-	-	2160	-	-	-	-
NL	-	1400	-	-	4250	0	-	-	1000	-	-	-
PL	-	-	-	800	2500	1200	-	-	-	-	-	-
PT	-	-	-	-	-	-	3500	-	-	-	-	-

Table B.19: Trading capacity between the market areas in GW for the year 2030. Values based on ENTSO-E (2020, 2018); German TSOs (2019) and historical values based on the yearly average of the day-ahead NTCs from ENTSO-E (2021).

From \ To	**AT**	**BE**	**CH**	**CZ**	**DE**	**DK**	**ES**	**FR**	**GB**	**IT**	**NL**	**PL**
AT	-	-	1700	1000	7500	-	-	-	-	1655	-	-
BE	-	-	-	-	2000	-	-	2800	1000	-	3400	-
CH	1700	-	-	-	5700	-	-	1300	-	6000	-	-
CZ	1200	-	-	-	2600	-	-	-	-	-	-	600
DE	7500	2000	4300	2000	-	4500	-	4800	2800	-	5500	2000
DK	-	-	-	-	4485	-	-	-	1400	-	700	1200
ES	-	-	-	-	-	-	-	5000	-	-	-	-
FR	-	4300	3700	-	4800	-	5000	-	6900	4350	-	-
GB	-	1000	-	-	1400	1400	-	6900	-	-	1000	-
IT	850	-	3700	-	-	-	-	2160	-	-	-	-
NL	-	3400	-	-	5500	700	-	-	1000	-	-	-
PL	-	-	-	800	3000	1200	-	-	-	-	-	-
PT	-	-	-	-	-	-	3500	-	-	-	-	-

Table B.20: Trading capacity between the market areas in GW for the year 2040. Values based on ENTSO-E (2020, 2018); German TSOs (2019) and historical values based on the yearly average of the day-ahead NTCs from ENTSO-E (2021).

From \ To	**AT**	**BE**	**CH**	**CZ**	**DE**	**DK**	**ES**	**FR**	**GB**	**IT**	**NL**	**PL**
AT	-	-	1700	1000	7800	-	-	-	-	1846	-	-
BE	-	-	-	-	2000	-	-	4000	2800	-	4800	-
CH	1700	-	-	-	7000	-	-	2500	-	6150	-	-
CZ	1200	-	-	-	4500	-	-	-	-	-	-	600
DE	7800	2000	5986	3900	-	5700	-	6600	1400	-	6200	3800
DK	-	-	-	-	5685	-	-	-	1400	-	700	1200
ES	-	-	-	-	-	-	-	8600	-	-	-	-
FR	-	5500	4900	-	6600	-	8600	-	7600	5300	-	-
GB	-	2800	-	-	1400	1400	-	7600	-	-	2800	-
IT	1666	-	4100	-	-	-	-	3200	-	-	-	-
NL	-	4800	-	-	6200	700	-	-	2800	-	-	-
PL	-	-	-	800	3000	1200	-	-	-	-	-	-
PT	-	-	-	-	-	-	5129	-	-	-	-	-

Appendix C. Additional Results: Cross-border Flows

Table C.21: Historical electricity trading between Italy and its directly connected markets. (ENTSO-E, 2021)

[TWh]	**Import**	**Export**	**Net Export**	**Import/Export ratio**
2015	45.63	4.38	-41.25	10.43
2016	40.45	7.79	-32.66	5.19
2017	44.03	6.34	-37.69	6.95
2018	47.89	3.73	-44.17	12.85
2019	45.12	6.65	-38.47	6.79

Table C.22: Cumulated yearly net export flows from France to Germany based on simulation results.

[TWh]	**High**		**Low**	
	Market	**Policy**	**Market**	**Policy**
2025	0.23	0.26	0.81	0.86
2030	1.85	1.86	2.52	2.50
2035	-10.48	-8.24	-10.49	-8.45
2040	-7.87	-2.84	-7.04	-1.89
2045	-2.96	1.61	-2.01	3.31
2050	1.40	4.57	2.06	4.23

Table C.23: Cumulated yearly net export flows from France to Switzerland based on simulation results.

[TWh]	**High**		**Low**	
	Market	**Policy**	**Market**	**Policy**
2025	19.86	19.84	20.18	20.13
2030	16.74	16.74	17.21	17.19
2035	10.59	12.20	10.87	12.55
2040	9.77	12.62	9.74	13.55
2045	11.55	14.09	11.66	15.45
2050	12.30	13.80	12.16	14.39

Table C.24: Cumulated yearly net export flows from France to Belgium based on simulation results.

[TWh]	High		Low	
	Market	**Policy**	**Market**	**Policy**
2025	3.60	3.58	3.87	3.81
2030	5.75	5.78	6.27	6.26
2035	-0.16	1.47	-0.52	1.25
2040	4.59	6.60	4.24	6.99
2045	7.31	9.30	6.46	9.86
2050	9.52	11.29	9.14	11.10

Table C.25: Cumulated yearly net export flows from France to Italy based on simulation results.

[TWh]	High		Low	
	Market	**Policy**	**Market**	**Policy**
2025	35.34	35.33	35.32	35.30
2030	31.06	31.12	31.47	31.42
2035	25.50	26.88	26.09	27.77
2040	19.26	23.62	19.30	23.47
2045	18.40	21.77	18.74	21.93
2050	17.17	19.36	16.52	19.62

Table C.26: Cumulated yearly net export flows from France to Spain based on simulation results.

[TWh]	High		Low	
	Market	**Policy**	**Market**	**Policy**
2025	0.77	0.92	0.33	0.40
2030	-17.58	-17.56	-17.48	-17.54
2035	-23.97	-23.07	-23.72	-22.65
2040	-28.53	-25.04	-28.16	-25.70
2045	-24.86	-22.70	-24.83	-22.80
2050	-18.37	-17.09	-19.19	-16.68

Table C.27: Cumulated yearly net export flows from France to Great Britain based on simulation results.

[TWh]	**High**		**Low**	
	Market	**Policy**	**Market**	**Policy**
2025	17.86	17.71	17.68	17.78
2030	19.80	19.79	18.40	18.50
2035	5.33	7.44	2.54	3.23
2040	9.56	10.70	6.97	10.69
2045	7.70	10.27	6.44	10.59
2050	7.45	9.82	6.94	9.46

Appendix D. Additional Results: Prices

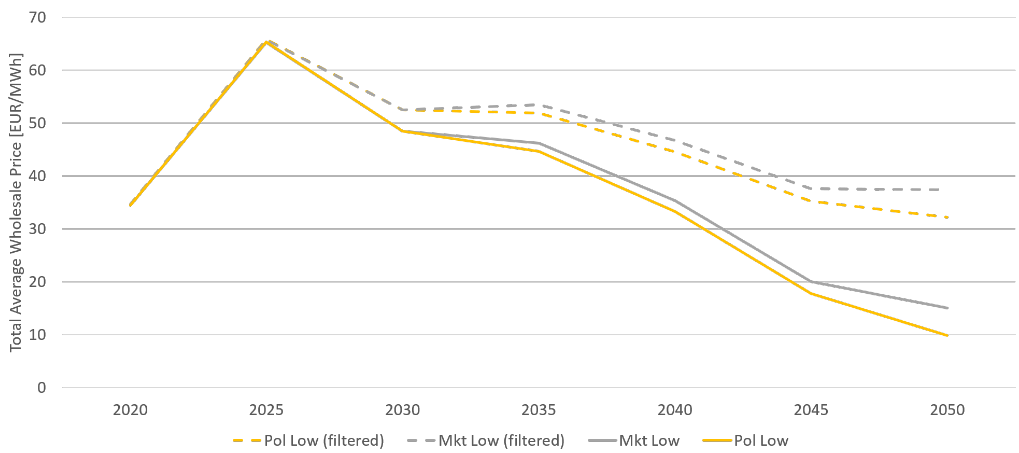

Figure D.11: Unweighted annual average wholesale spot market prices for France and the neighboring market areas in the Low sensitivity. The lines depict average prices for the scenarios. The dashed lines show the average prices for the different scenarios when the negative prices are filtered out and set to zero. The year 2020 shows historical values based on ENTSO-E (2021). None of the prices take into account levies for Gid, RES, or CRM.

Table D.28: Annual arithmetic mean of spot market prices historically (2015 and 2020 based on ENTSO-E (2021) day-ahead auction results) and simulated (from 2025) for France and the neighboring market areas for the Market High Scenario. None of the prices take into account levies for Gid, RES, or CRM.

[EUR/MWh]	**FR**	**DE**	**BE**	**CH**	**ES**	**GB**	**IT**
2015	38.47	31.63	44.68	40.18	50.32	55.33	52.19
2020	32.11	30.40	31.78	33.87	33.87	41.39	37.66
2025	64.01	63.54	65.03	68.18	57.81	66.92	77.19
2030	51.12	49.33	51.26	56.79	24.84	55.81	63.05
2035	52.25	43.97	49.93	57.01	25.29	52.53	66.44
2040	40.60	34.94	39.98	45.35	19.29	41.72	52.64
2050	13.57	13.98	17.19	17.50	1.28	17.59	26.91

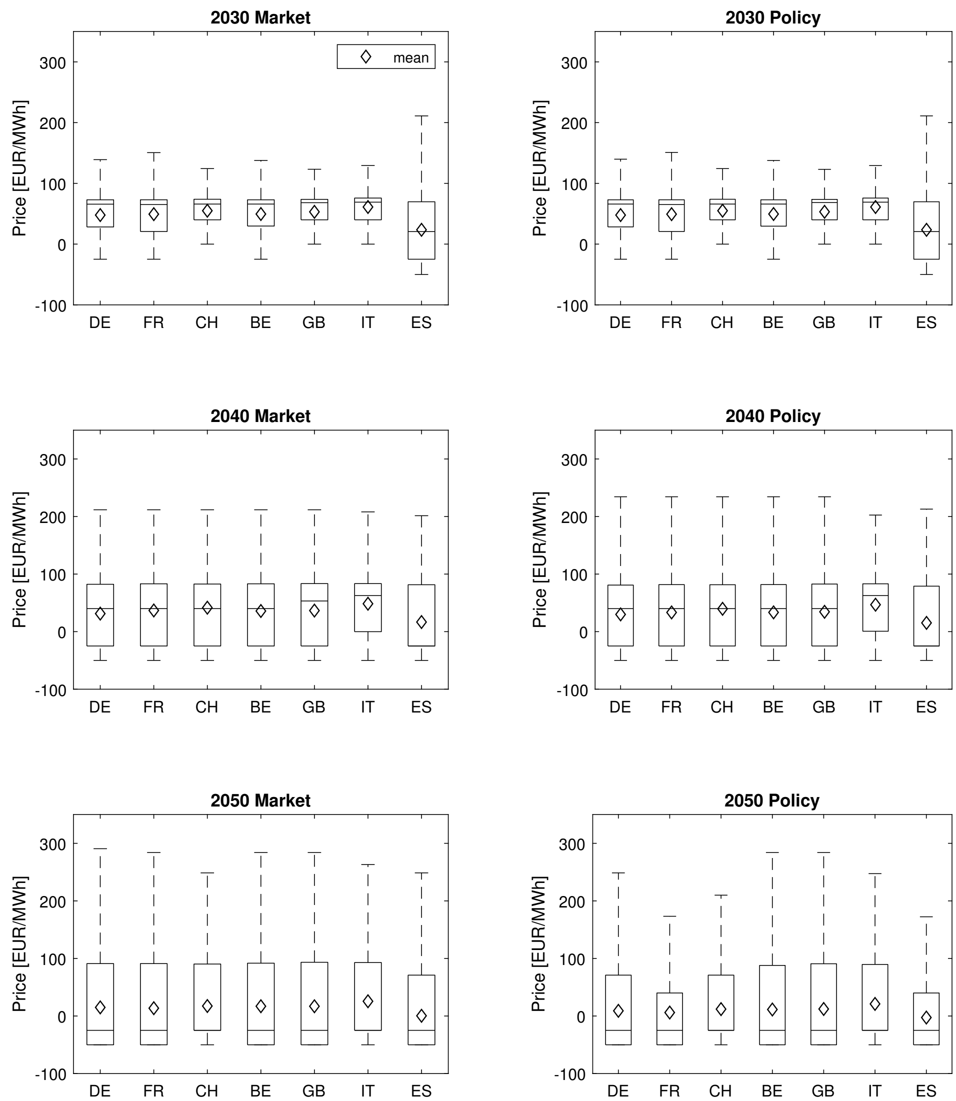

Figure D.12: Box plots of wholesale prices between 2030 and 2050 for all market areas surrounding France for the Low sensitivity. For a better visualization, the outliers are not shown. The average is indicated as diamond. None of the prices take into account levies for Gid, RES, or CRM.

Table D.29: Annual arithmetic mean of spot market prices historically (2015 and 2020 based on ENTSO-E (2021) day-ahead auction results) and simulated (from 2025) for France and the neighboring market areas for the Market Low Scenario. None of the prices take into account levies for Gid, RES, or CRM.

[EUR/MWh]	FR	DE	BE	CH	ES	GB	IT
2015	38.47	31.63	44.68	40.18	50.32	55.33	52.19
2020	32.11	30.40	31.78	33.87	33.87	41.39	37.66
2025	63.25	63.17	64.29	67.28	56.76	66.06	75.86
2030	49.30	47.80	49.53	54.94	23.54	53.09	61.09
2035	48.90	40.85	46.46	53.76	22.93	48.08	62.49
2040	36.80	31.32	35.87	41.61	16.67	36.60	48.49
2050	13.56	14.95	16.96	17.36	0.36	16.93	25.60

Table D.30: Annual arithmetic mean of spot market prices historically (2015 and 2020 based on ENTSO-E (2021) day-ahead auction results) and simulated (from 2025) for France and the neighboring market areas for the Policy High Scenario. None of the prices take into account levies for Gid, RES, or CRM.

[EUR/MWh]	FR	DE	BE	CH	ES	GB	IT
2015	38.47	31.63	44.68	40.18	50.32	55.33	52.19
2020	32.11	30.40	31.78	33.87	33.87	41.39	37.66
2025	64.04	63.60	65.09	68.14	57.78	66.93	77.18
2030	51.14	49.42	51.30	56.77	24.90	55.87	63.14
2035	50.86	43.53	49.14	56.04	24.69	51.87	65.89
2040	35.14	31.61	35.45	40.89	17.01	36.65	49.17
2050	8.41	12.36	14.57	14.25	-0.85	15.96	24.55

Table D.31: Annual arithmetic mean of spot market prices historically (2015 and 2020 based on ENTSO-E (2021) day-ahead auction results) and simulated (from 2025) for France and the neighboring market areas for the Policy Low Scenario. None of the prices take into account levies for Gid, RES, or CRM.

[EUR/MWh]	FR	DE	BE	CH	ES	GB	IT
2015	38.47	31.63	44.68	40.18	50.32	55.33	52.19
2020	32.11	30.40	31.78	33.87	33.87	41.39	37.66
2025	63.31	63.16	64.33	67.35	56.82	66.11	75.97
2030	49.31	47.79	49.54	54.96	23.52	53.16	61.06
2035	46.62	39.59	44.78	51.94	21.96	45.98	61.40
2040	33.37	29.95	33.46	39.66	15.21	34.44	46.81
2050	6.03	9.00	11.29	11.98	-2.66	12.19	20.99

Appendix E. Additional Results: Market Price Correlations

Table E.32: Correlation coefficient between hourly market prices of the neighboring market areas around France in the year shown based on the Policy High Scenario. 2020 values based on historical day-ahead auction market prices taken from ENTSO-E (2021).

Correlation coefficient		**2020**	**2030**	**2040**	**2050**
CH	FR	0.94	0.91	0.93	0.92
CH	DE	0.85	0.88	0.92	0.87
FR	DE	0.88	0.93	0.90	0.80
CH	IT	0.90	0.85	0.85	0.78
FR	IT	0.87	0.77	0.79	0.74
DE	IT	0.76	0.73	0.75	0.65
FR	ES	0.78	0.53	0.66	0.62
FR	BE	0.94	0.96	0.94	0.90
CH	BE	0.91	0.91	0.92	0.89
CH	ES	0.77	0.48	0.59	0.52
DE	ES	0.63	0.45	0.53	0.35
DE	BE	0.90	0.96	0.93	0.88
ES	BE	0.71	0.49	0.59	0.49
IT	BE	0.83	0.76	0.76	0.69
IT	ES	0.76	0.47	0.56	0.53
GB	FR	0.76	0.89	0.90	0.82
GB	ES	0.58	0.42	0.55	0.42
GB	DE	0.67	0.87	0.88	0.81
GB	CH	0.73	0.81	0.87	0.80
GB	IT	0.70	0.66	0.71	0.60
GB	BE	0.76	0.90	0.95	0.91
Sum		**16.62**	**15.63**	**16.49**	**14.99**

Table E.33: Correlation coefficient between hourly market prices of the neighboring market areas around France in the year shown based on the Market Low Scenario. 2020 values based on historical day-ahead auction market prices taken from ENTSO-E (2021).

Correlation coefficient		**2020**	**2030**	**2040**	**2050**
CH	FR	0.94	0.91	0.93	0.92
CH	DE	0.85	0.88	0.90	0.81
FR	DE	0.88	0.93	0.88	0.74
CH	IT	0.90	0.84	0.86	0.81
FR	IT	0.87	0.76	0.80	0.77
DE	IT	0.76	0.73	0.75	0.63
FR	ES	0.78	0.53	0.64	0.59
FR	BE	0.94	0.97	0.94	0.91
CH	BE	0.91	0.90	0.91	0.89
CH	ES	0.77	0.48	0.58	0.50
DE	ES	0.63	0.46	0.51	0.32
DE	BE	0.90	0.97	0.92	0.81
ES	BE	0.71	0.49	0.57	0.48
IT	BE	0.83	0.75	0.76	0.71
IT	ES	0.76	0.46	0.55	0.51
GB	FR	0.76	0.90	0.89	0.83
GB	ES	0.58	0.43	0.53	0.42
GB	DE	0.67	0.88	0.87	0.76
GB	CH	0.73	0.83	0.86	0.81
GB	IT	0.70	0.67	0.71	0.63
GB	BE	0.76	0.92	0.95	0.92
Sum		**16.62**	**15.67**	**16.35**	**14.78**

Table E.34: Correlation coefficient between hourly market prices of the neighboring market areas around France in the year shown based on the Market High Scenario. 2020 values based on historical day-ahead auction market prices taken from ENTSO-E (2021).

Correlation coefficient		**2020**	**2030**	**2040**	**2050**
CH	FR	0.94	0.91	0.94	0.92
CH	DE	0.85	0.87	0.90	0.86
FR	DE	0.88	0.92	0.88	0.79
CH	IT	0.90	0.85	0.86	0.80
FR	IT	0.87	0.77	0.80	0.76
DE	IT	0.76	0.73	0.75	0.66
FR	ES	0.78	0.53	0.64	0.60
FR	BE	0.94	0.96	0.95	0.91
CH	BE	0.91	0.90	0.92	0.90
CH	ES	0.77	0.48	0.59	0.51
DE	ES	0.63	0.45	0.51	0.35
DE	BE	0.90	0.96	0.92	0.85
ES	BE	0.71	0.49	0.58	0.50
IT	BE	0.83	0.76	0.77	0.71
IT	ES	0.76	0.47	0.55	0.51
GB	FR	0.76	0.89	0.89	0.84
GB	ES	0.58	0.42	0.53	0.43
GB	DE	0.67	0.87	0.87	0.79
GB	CH	0.73	0.81	0.86	0.81
GB	IT	0.70	0.66	0.72	0.63
GB	BE	0.76	0.91	0.95	0.92
Sum		**16.62**	**15.63**	**16.39**	**15.03**

Appendix F. Additional Results: Capacity Development

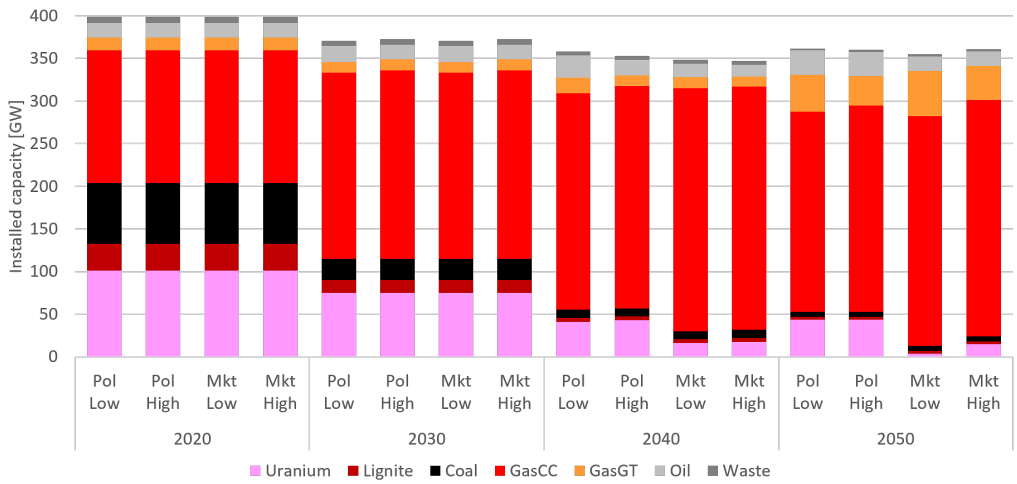

Figure F.13: Simulated installed capacity development of flexible power plants of all considered market areas.

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