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Impact of the phase out of French nuclear plants on the Spanish electricity market.

Master Thesis submitted for the degree of

Master in Economics: Empirical Application and Policies

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List of Abbreviations

- AD: Aggregate Demand.
- AS: Aggregate Supply.
- ENTSO-E: European Network of Transmission System Operators for Electricity.
- GW: Gigawatt.
- MIBEL: Iberian Electricity Market.
- MSP: Marginal System Price.
- MTV: Maximum Tradable Volume.
- MW: Megawatt.
- MWh: Megawatt- hour.
- OMIE: Iberian Energy Market Operator.
- PNIEC: National Integrated Energy and Climate Plan.
- REE: Electricity Network in Spain (Red Eléctrica de España).
- RES-E: Electricity from Renewable Energy Sources.
- RES: Renewable Energy Sources.
- TW: Terawatt.
- TWh: Terawatt- hour.

Abstract

One of the key elements in the transition to low carbon economies is the phase-out of fossil-fuel based technologies. Nuclear power, despite not being a high emitting source, is one of the technologies at the heart of the debate, mainly due to security issues. However, nuclear electricity generation is still one of the baseload technologies in many countries and its progressive phase-out will thus have important economic implications. In particular, France, which is one of the countries with the highest nuclear participation worldwide (i.e. 70.6% of total generation), decided to lower nuclear production to 50% of total generation by 2035. Since France is a very well interconnected country in terms of energy, and it is also a net electricity exporter, the prices of all the neighbour electricity markets will also be affected by this political decision. Bianco and Scarpa (2018) analyzed the effect that the reduction of the import of electricity from France to Italy due to the phase-out of French nuclear plants had on the Italian electricity market when the interconnection size was 2,650 MW. In this master thesis we propose to explore the effect that this phase-out would have on the Spanish electricity market, where the current electricity flow from one country to another is 2,800 MW. In fact, France already experienced a major supply crisis in January 2017 due to the stoppage of a large part of its nuclear plants. In that moment, France had to import Spanish electricity to cover their demand and Spanish electricity prices increased by a 28% compared to the same month of the previous year. Our results would have interesting policy implications for the integration of the single European electricity market, which is in the European 2030 agenda. The results show that the reduction of nuclear energy in France, increase the prices and decrease the quantities, but reducing a 100% of coal and increasing the interconnection capacity to the maximum and the production of renewable energies, the prices tends to decrease and quantities increase again. Hence, this paper recommends supporting the reduction of coal and an increase in interconnection capacity and renewable energies as a way to counteract the increase in the prices due to the phase-out of French nuclear energy.

Key words: Energy market, nuclear energy, interconnection.

1 Introduction

Spain is practically an energy island and its only interconnections with Europe are through France, according to the Electricity Network in Spain (REE, for its Spanish acronym), this interconnection capacity is currently 2,800 MW. In fact, one of the goals of the European Union in the next years is to create the "Energy Union", for which increasing the size of the interconnections all over Europe is a priority. In this regard, the National Integrated Energy and Climate Plan (PNIEC, for its Spanish acronym) for 2021- 2030 aims to increase the interconnection capacity between Spain and France to 8,000 MW, that increase represents more than 200% over existing levels.

On the other hand, another key element of the European energy policy for the following decades is the transition to a low carbon economy. The use of Renewable Energy Sources (RES) will be fostered and fossil fuels will be gradually phased-out, which also includes nuclear power. In this sense, the French nuclear fleet is currently the second largest in the world in terms of installed capacity, only after USA, it is composed of 56 nuclear reactors, distributed among 18 power plants. In 2019, production was 379.5 TWh, or 70.6% of electricity production in France (CDE 2019).

The French Law for "Energy Transition and Green Growth" is a law with multiple objectives where one is mentioned to "Preserving human health and the environment, mitigating the emission of greenhouse gases, limiting industrial risks, reducing the exposure of citizens to air pollution and ensuring nuclear safety". In November 2019, the "Energy and climate" law of France published plans to reduce this participation of nuclear energy to 50% by 2035, following the European directives.

Since France is the main interconnection between Spain and Europe, any change in French electricity prices would have an impact on Spanish electricity prices (and vice versa). In fact, the profit from the interconnection between Spain and France in 2019 was 168 million of euros (24.1% less compared to the previous year). In this sense, reducing nuclear production in France would affect the electricity price in Spain. According to this research, with the increase of the interconnections capacity to the maximum, the profit will be 1,276.96 million of euros.

A first analyzes of the case of a German nuclear phase-out in the context of the internal electricity market in Europe by Hoster (1998) found that in the long term the phase-out would only lead to a moderate increase in the average costs of electricity generation but in a competitive integrated electricity market, costs are significantly lower than in closed electricity markets. More recently, Bianco and Scarpa (2018) carried out a research about the impact of the phase-out of French nuclear plants on the Italian power sector, showing the relevance of this situation for Italian energy security, because a large part of the electricity that Italy uses is imported from France, but a future elimination of nuclear power plants will significantly reduce export capacities with substantial consequences on the Italian energy system.

Given this situation, it is extremely important to carry out an analysis of the effect of the phase-out of French nuclear plants on the Spanish electricity market, taking into account the expected changes in the interconnection. This research aims fills the gap for the Iberian market and answers the following question: "What will happen to the Spanish electricity prices when the phase-out of French nuclear plants?". In order to answer the research question the objective of this work is to quantify the impact of the phase-out of French nuclear plants on the Spanish electricity market.

We take 2019 as the study year since it is the most recent year with complete hourly data and they are accessible, because they are downloaded from the website of the electricity market operator designated for the management of the daily electricity market in the Iberian Peninsula and from the European Network of Transmission System Operators for Electricity (ENTSO-E) website.

Taking the idea of Bianco and Scarpa (2018), in this paper we carry out a similar analysis for the effect of the phase-out of French nuclear plants on the Spanish electricity market. To develop this research, we combine two different methodologies that have already been used by other authors. On the one hand, we use the algorithm elaborated by Ciarreta, Espinosa and Pizarro-Irizar (2014) to compute the outcome of the hourly auction for the electricity whole sale market. On the other hand, we use the idea of "synthetic bidding" employed by Ciarreta, Espinosa and Pizarro-Irizar (2017), in order to build "synthetic" supply curves for different scenarios of interconnections, renewable capacity, nuclear phase-out and changes in interconnections.

The contribution of this work consists of measuring the effect of the phase-out of French nuclear plants on the Spanish electricity market, and will also serve as the basis for subsequent researches who could take more years into account, focus on the technologies or continue the analysis of the effect as the French target for 2035 is met. Our results will contribute to the energy policy analysis that is being conducted in Europe to achieve a transition to a low carbon economy at the lowest cost.

The rest of the article is organized as follows: Section 2 presents a literature review including interconnections and nuclear phase-out in Europe. Section 3 exposes theoretical framework with the current situation of the nuclear phase-out in France and electricity market in Spain, where market prices and the importance of doing this research are analyzed. Section 4, details the empirical strategy carried out. Section 5 presents the main results. Section 6 ends the research with conclusion and some policy implications.

2 Literature Review

Reviewing previous publications about interconnections, Child at all (2019) analyzes the importance of flexible electricity generation, interconnections, and storage to obtain fully renewable electricity systems through two scenarios, the first one, by independently modeled regions and the second one, taking into account the interconnection between regions. They mention that when making the transition to renewable energy the first region presented a reduction in price, but in the second scenario, in which the regions are interconnected the electricity price is even lower. The results of these scenarios verify the increased cost savings. The second scenario, which considers the interconnections between regions, presents savings of 26 billion euros per year compared to the scenario modeled independently, they say that "more rapid defossilisation and greater cost savings can be achieved through the establishment of increased interconnections between the regions of Europe".

The authors mention France as the country with the highest participation of nuclear energy over the total energy production in the European Union, so its energy policies affect the countries with which it is connected energetically and their study shows that by incorporating low costs of generation and storage of renewable energy and choosing the right support instruments and in line with the objectives of the European Union, a transition towards energy sustainability in Europe can be reached.

Continuing with the interconnections, Ries, Gaudard, and Romerio (2016) analyze the case of Malta and its interconnection with the European market by building merit order curves. They conclude that the price level of electricity per consumer does not decrease with the newly installed interconnection but also depends on installed generating capacity, oil price, and market design.

Their study mentions the security of energy supply and the negative effects of infrastructure projects as two important points that should not be ignored by decision makers when implementing policies. Among their recommendations, they mention the importance that should be given to increasing interconnections as well as replacing old generators.

Leaving aside the interconnections, but taking into account France's phase-out policies, we find Malischek and Trüby, (2016), they analyze the phase-out of nuclear energy in France in three aspects, first, the costs of phasing out nuclear power in France, second, how much of the costs will be passed on to the rest of the European power system and third, what effect does the uncertainty regarding future nuclear policy in France have on system costs. Among their results, they mention that the additional cost of phasing out nuclear power in France will be 76 billion euros and that this cost is higher if the phase-out of the nuclear power plants occurs before the end of the technical lifetime. The costs for the European electricity system depend on how quickly neighboring countries implement policies to counteract the phase-out of french nuclear plants, and they highlight the importance of a coordinated policy among European countries. The costs of uncertainty would be at most 6 billion euros, and these costs are lower than the cost of the phasing out of nuclear plants.

Finally, analyzing the phase-out policy of nuclear energy and the interconnections we find Bianco and Scarpa (2018), using a bid stack model they build sixteen scenarios with different assumptions trying to measure the effects of the phase-out of French nuclear plants on the Italian electricity market. The paper mentions the importance of studying possible investments to counteract the replacement of older power plants with newer and more efficient ones before the system comes under too much pressure and pays much attention to estimating the amount of additional generation that can be added to the Italian electricity system. They also found an increase in price from 118 euros per MWh to 132 euros per MWh.

Rinne (2018), however, has measured the nuclear energy plants outages to Germany prices, among the results, it mentions that it not only affects the prices in Germany but also the German- Austrian electricity prices. The French day-ahead electricity price increased by 14.15 euros per MWh due to the extensive inspections. Due to the increased electricity exports from Germany to France, the German-Austrian electricity price increased by 1.72 euros per MWh.

Among its results, the study also mentions the importance of diversification of electricity production as a way to counteract the effect of rising prices and that European electricity markets would benefit from an extension of the cross-border trade as a policy to maintain supply at lower costs.

Finally, Osorio and Ackere, (2016) analyze the effect of replacing nuclear energy with renewable energy in Switzerland, the results show that nuclear energy is mainly replaced by photovoltaic energy and imports. Switzerland has been a net exporter, but imports are expected to increase until Switzerland becomes a net importer.

Changes in the composition of electricity production technologies in Switzerland, in addition to the exchange patterns, cause an increase in price of 17 Swiss francs (CHF) per MWh, but with the cross-border capacity expansion, prices would decrease. Furthermore, they recommend the incentive to produce renewable energy without discouraging investment in other technologies.

As analyzed in this section, the theoretical framework gives strong support to interconnections, either to reduce prices or to increase cost savings. In addition, the different countries mentioned analyze the impact that the phase-out of French nuclear plants or their own nuclear plants may have, most of them try to counteract the effects of the price increase by increasing interconnections and stimulating investment in the diversification of the productive matrix, especially in renewable energies. There is still a gap in the research of the phase-out effect of French nuclear energy on the Spanish electricity market and this document attempts to fill that gap.

3 Descriptive analysis of the electricity market in Spain and France

In this section we describe the characteristics of nuclear production in France (Section 3.1), the main features of the Spanish electricity interconnection with France (Section 3.2) and a descriptive analysis of the Spanish electricity prices formation (Section 3.3).

3.1 Nuclear production in France

Currently, with an installed capacity of almost 61.4 GW, the French nuclear fleet is the second largest in the world in terms of installed capacity, only after USA. In 2019, it produced 379.5 TWh of electricity, or 70.6% of total electricity production in France. This is 3.5% less than in 2018, due to the lower availability of reactors. The average annual production of the French nuclear fleet is slightly less than 400 TWh (DCE 2019).

The French nuclear fleet has 56 operating nuclear reactors distributed across 18 power plants, following the closure of the 2 reactors at the Fessenheim power plant in February and June 2020 (14 reactors have already been shut down in the past), France plans to reduce the participation of nuclear energy to 50% by 2035.

The closure of these nuclear plants is part of an energy strategy to rely more on renewable energy sources such as solar and wind power, that is, as nuclear power plants are closed in France, the energy demand will be covered by renewable energies that also guarantee the care of the environment. These plans also include the closure of coal plants (Digges, 2020).

3.2 The Spanish electricity interconnection with France

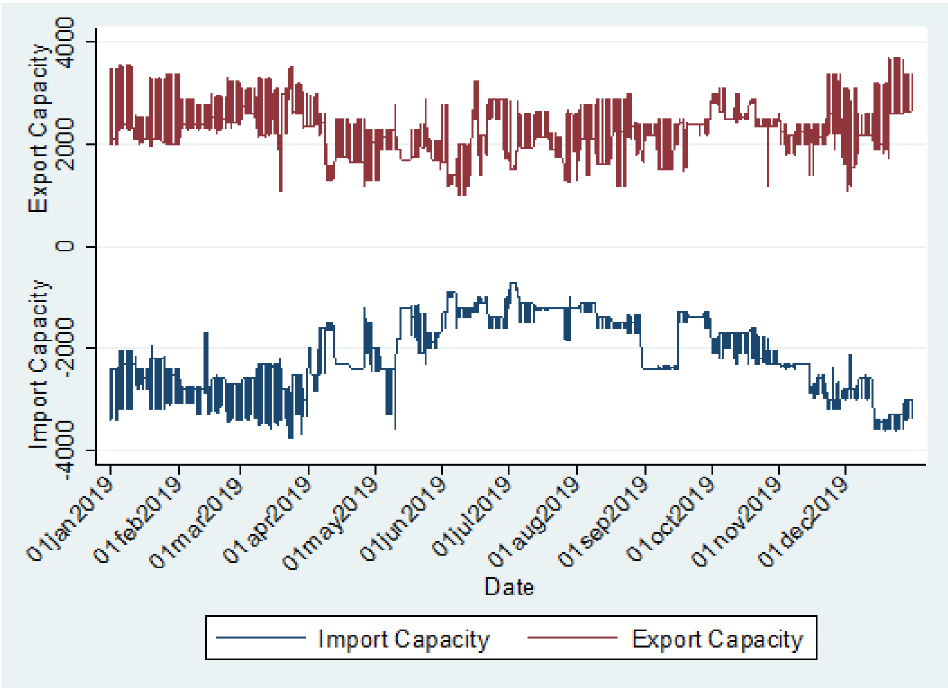
Spain is considered an energy island, because its only electric interconnections with Europe are through France. According to the Electricity Network in Spain (REE, for its Spanish acronym), this interconnection capacity is currently 2,800 MW. The PNIEC 2021- 2030 aims to increase this interconnection capacity to 8,000 MW.

For its part, OMIE (2019) in its annual report has mentioned that during 2019, the total energy traded in the daily and intraday markets was 267 TWh (4% less compared to the previous year). The economic volume of purchases traded in the markets managed by OMIE in 2019 was 12,979 million of euros, (19.6% less compared to the previous year), of which 10,308 million of euros correspond to purchases in the Spanish area (20.4% less compared to the previous year). Another relevant characteristic of the Spanish electricity market is the profit from the interconnection between Spain and France, which in 2019 was 168 million of euros (24.1% less compared to the previous year).

Figure 1, that represents the import and export capacity during 2019 (in MW), shows how the interconnection capacity with France has been used, the red line shows the use of exports and the blue line corresponds to imports. It can be seen that in many hours the total capacity is used (as mentioned before it is 2,800 MW). There are other periods in which the use of the interconnection is less, but even there is a constant use of the interconnection and, is expected to see that changes in this interconnection, its capacity (increasing or reducing) or the energy coming from France, will affect Spain prices.

Given this situation, the present work aims to measure the effect of the phase-out of French nuclear plants on the Spanish electricity market.

Figure 1: Import and Export Capacity during 2019 (MW).



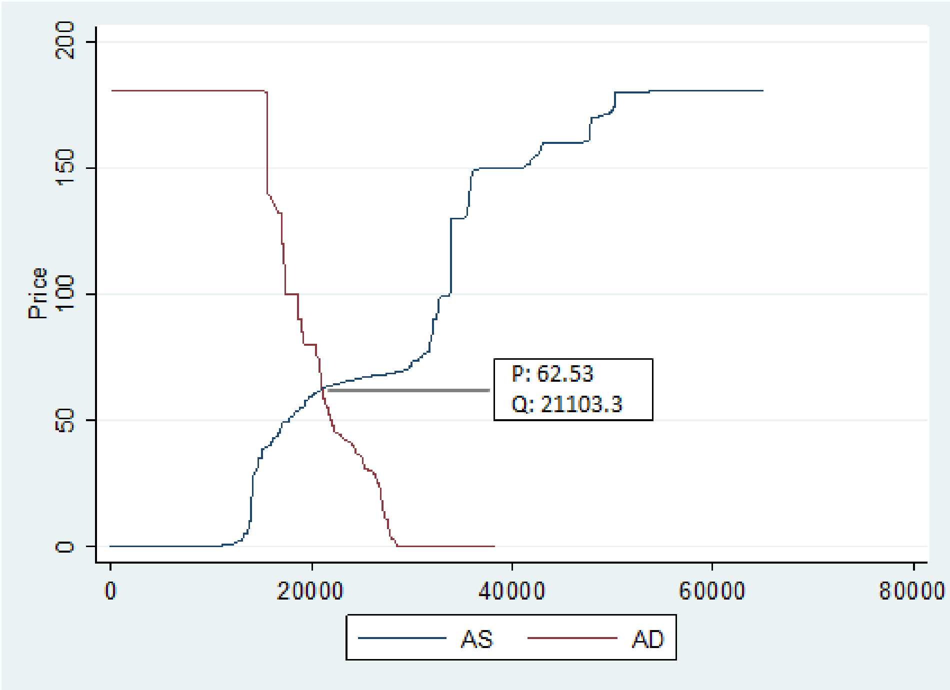
Source: Own elaboration with data from OMIE.

3.3 Analysis of the price formation in the Spanish electricity market

In this section we analyze the price formation in the Spanish day-ahead market. Two reference days have been taken to carry out this section, one winter day and another, summer day. On the one hand, the winter reference day, the second Wednesday of February (February 13^{th}), in off-peak (3am) and on-peak (9pm).

To start, Figure 2 shows the aggregate demand and aggregate supply on February 13^{th} at 3am, indicates that on that day at off-peak the equilibrium price was 62.53 euros per MWh and the equilibrium quantity was 21,103.3 MWh.

Figure 2: Aggregate Demand and Aggregate Supply on February 13^{th}, at 3am.



Source: Own elaboration with data from OMIE.

Continuing with the same winter reference day, Figure 3 shows the aggregate demand and aggregate supply on February 13^{th} at 9pm, indicates that on that day at on-peak the equilibrium price was 51 euros per MWh and the equilibrium quantity was 35,221.5 MWh.

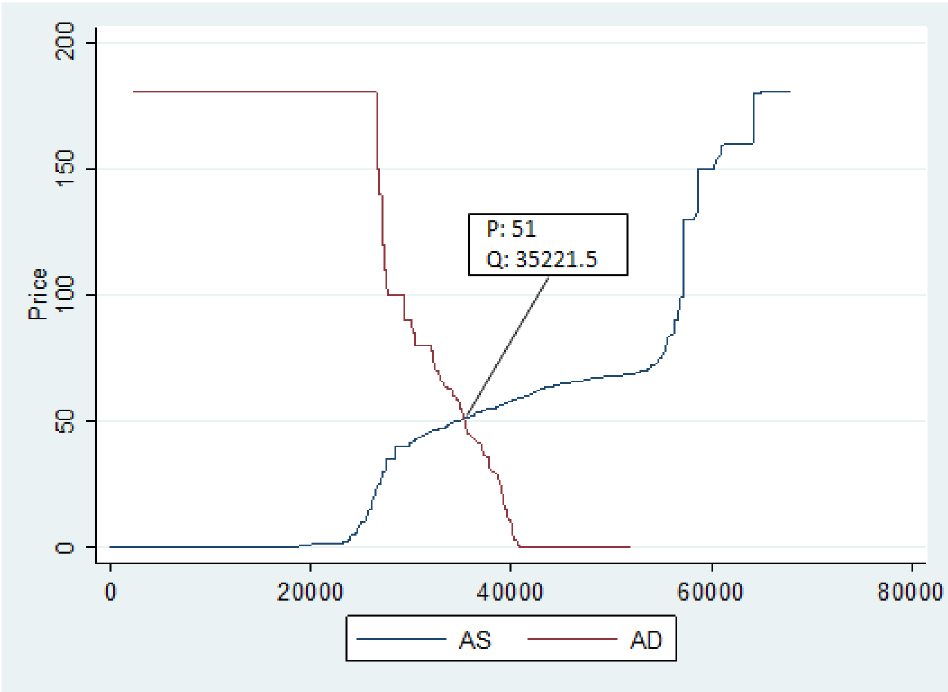
Comparing off-peak and on-peak of this winter reference day, it can be seen an increase in the equilibrium quantity and the prices are lower. It is also observed that the section in which the price is zero is longer in the aggregate demand and aggregate supply curves of the on-peak, that means cheaper energy prices at that time.

Furthermore, after a visual inspection of the slopes, it could be said that the elasticities are greater in the aggregate supply curve than in the aggregate demand curve, means that the quantity supplied is more sensitive to the variation in prices.

However, the aggregate supply curve both off-peak and on-peak show a more variable behavior in terms of their elasticities, after passing the section where the price is zero, the elasticity is low, but near the point of equilibrium elasticity increase until a certain point after equilibrium and then, decrease again.

On the other hand, taking into account the summer reference day, the second Wednesday of September (September 11^{th}- summer), in off-peak (3am) and on-peak (9pm) was analized. Figure 4 shows the aggregate demand and aggregate supply on September 11^{th} at 3am, indicates that on that day at off-peak the equilibrium price was 29.4 euros per MWh and the equilibrium quantity was 22,261.8 MWh.

Figure 3: Aggregate Demand and Aggregate Supply on February 13^{th}, at 9pm.



Source: Own elaboration with data from OMIE.

Continuing with the same summer reference day, Figure 5 shows the aggregate demand and aggregate supply on September 11^{th} at 9pm, indicates that on that day at on-peak the equilibrium price was 25.8 euros per MWh and the equilibrium quantity was 30,661.7 MWh.

Comparing off-peak and on-peak of this summer reference day, it can be seen an increase in the equilibrium quantity and the prices are lower. It is also observed that the section in which the price is zero is longer in the aggregate demand and aggregate supply curves of the on-peak, that is, the price of energy is cheaper at that time.

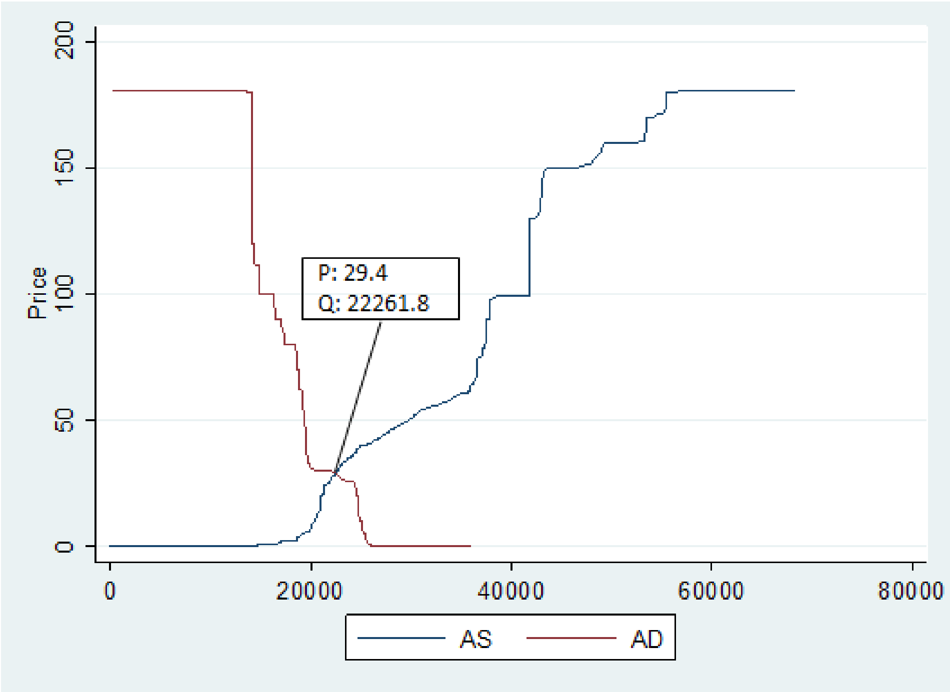
Furthermore, after a visual inspection of the slopes, it could be said that the elasticities are greater in the aggregate supply curve than in the aggregate demand curve, means that the quantity supplied is more sensitive to the variation in prices.

The aggregate supply curve corresponding to the on-peak (Figure 5) shows a similar behavior to the aggregate supply curves of the winter scenario. That is, after the zero price section, the elasticity is low and at values close to equilibrium, the elasticity increases until a certain point where it begins to decrease again.

now, taking both season scenarios into account, it has been found that the greatest variations between equilibrium prices and equilibrium quantities occur in the winter.

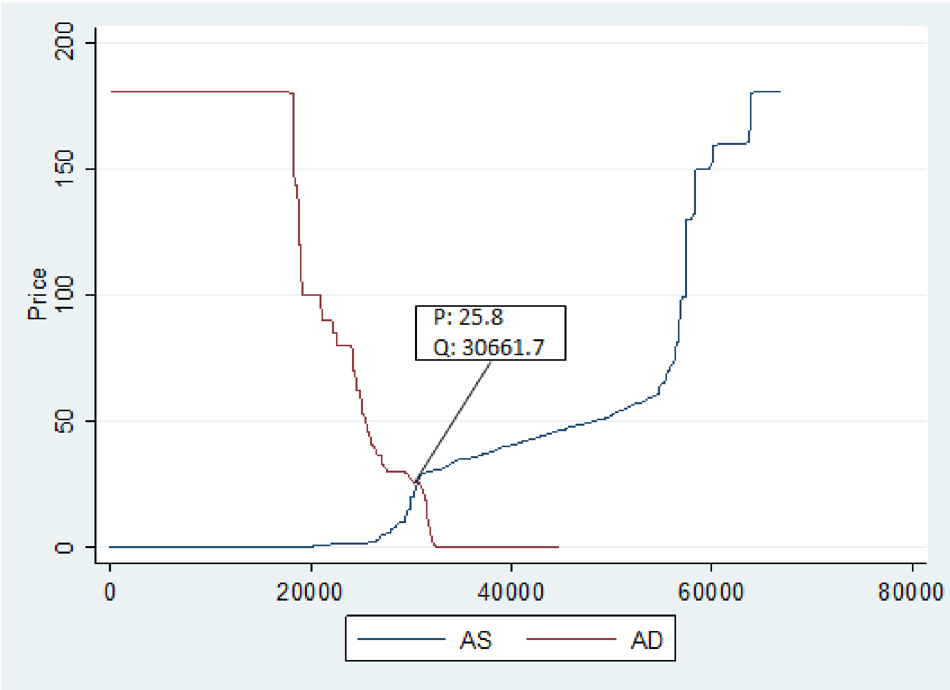
Once the equilibrium quantities and the equilibrium prices are described, the behavior of the Marginal System Price (MSP) is analyzed during the period of one year (2019), January to December, Figure 6 describes the results.

Figure 4: Aggregate Demand and Aggregate Supply on September 11^{th}, at 3am.



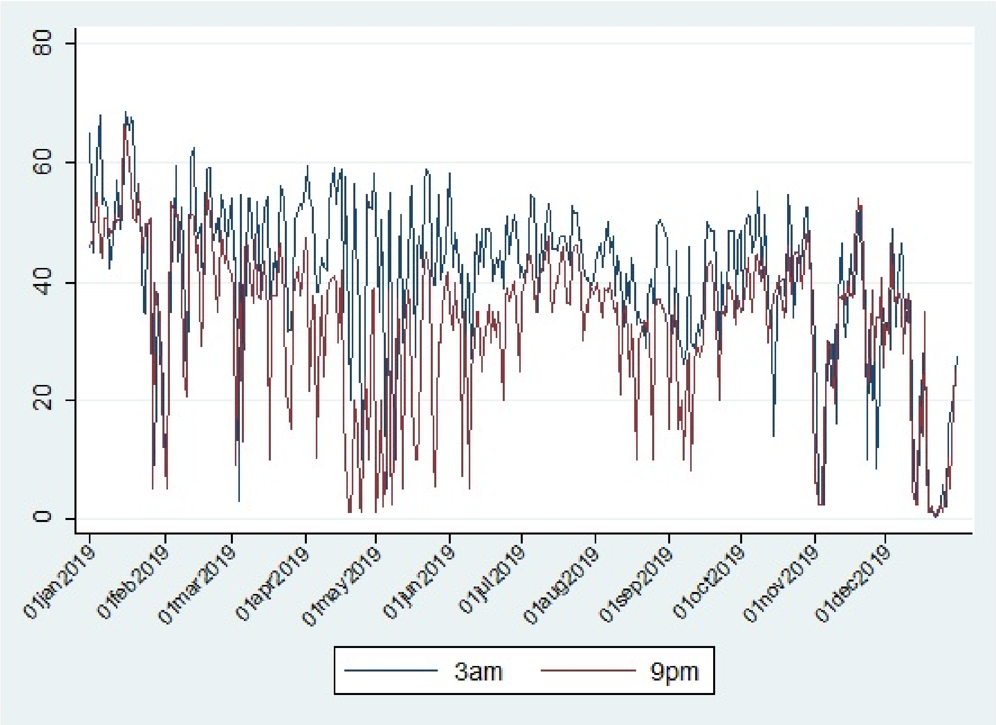
Source: Own elaboration with data from OMIE.

Figure 5: Aggregate Demand and Aggregate Supply on September 11^{th}, at 9pm.



Source: Own elaboration with data from OMIE.

Figure 6: Marginal System Price during 2019, at 3am and 9pm (euro per MWh).



Source: Own elaboration with data from OMIE.

The Figure 6 shows the behavior of the MSP during 2019, at off-peak (3am) and on-peak (9pm). The blue line, that corresponds to 3am or off-peak, is higher than the red line, that corresponds to 9pm or on-peak. The greatest variations are observed during the months of April and May, while the smallest variations are observed during the months of June, July and August. The months with the smallest gap between 3am MSP and 9pm MSP are October, November, December and January.

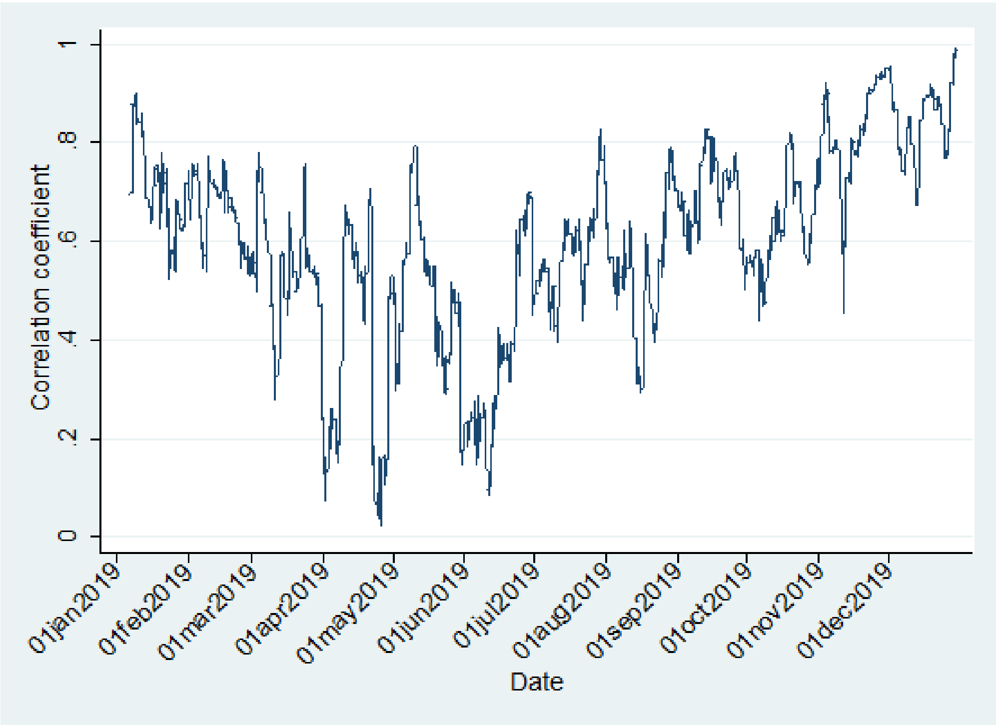
Continuing with the analysis of prices, has been made a calculation of the sliding or running window correlation between France electricity prices and Spanish electricity prices with a window of 168 (7 days and 24 hours).

Sliding-window cross-correlation is a common method to estimate time varying correlations between signals. It produces a correlation value between two signals (positive or negative) for every (time,lag) pair of values. In principle, the expected value of the correlation for any pair of (time,lag) values must be computed by averaging x(t) y(t+lag) over many realizations of the stochastic process (Bäcker & Cassenaer, 2002).

Figure 7 shows the sliding window correlation coefficients between France electricity market prices and Spain electricity market prices, in which it is observed that the results greater than zero (positive) and stable, in some cases very high with values above 0.8.

The positive results obtained indicate that the relationship between the price of electricity market in France and the price of electricity market in Spain is positive, that is, given an increase in prices in France (Spain), the prices in Spain (France) tend to increase, and given a decrease in prices in France (Spain), prices in Spain (France) tend to decrease. It can be seen that it is time-varying.

Figure 7: Sliding window correlation coefficients between France and Spain electricity prices.



Source: Own elaboration with data from OMIE.

4 Empirical Strategy and Data

In this section we describe the databases (4.1), the methodology used in our analysis, including the algortithm that we model (4.2) and the scenarios that we simulate (4.3).

4.1 Data

We use two different data sources for the preparation of this work. On the one side, we use historical data (ex-post) of the Spanish electricity hourly bids during 2019, which were extracted from the website of OMIE. The variables of this database are the following:

- Date: Day, month and year of the observation (Since January, 1^{st},2019 to December 31^{st}, 2019).
- Hour: Time the price was captured (1 am to 12 pm).
- quantity: energy bid in MWh by one production unit at a certain price.
- price: price bid in EUR/MWh by one production unit for a certain quantity of energy.

On the other hand, the database used for wholesale French and Spanish prices has been taken from the ENTSO-E website. The variables of this database are the following:

- Date: Day, month and year of the observation (Since January, 1^{st},2019 to December 31^{st}, 2019).
- Hour: Time the price was captured (1 am to 12 pm).
- price_sp: Price of the electricity in Spain.
- price_fr: Price of the electricity in France.

Once the price data for Spain and France have been extracted, the mean, standard deviation, maximum, minimum, skewness and kurtosis can be seen in the Table 1.

Comparing the results for the prices of Spain and France, it can be seen that the mean is higher for Spain with 47.8682, however, the standard deviation is higher in France with 14.0206. For Spain the maximum is 74.74 and the minimum 0.01, and for France the maximum is 121.46 and the minimum is -24.92, because in France negative prices are allowed.

The skewness negative coefficient indicates that prices in Spain present a negative or left-handed asymmetric distribution, while the positive coefficient of prices in France indicates that it presents a positive or right-handed asymmetric distribution. The kurtosis results indicate that prices in Spain, having the coefficient higher than prices in France, show a higher concentration of values around its mean.

Table 1: Descriptive statistics of electricity prices in Spain and France in 2019.

Descriptive Statistics	price_sp	price_fr
Mean	47.8682	39.4517
Standard Deviation	10.8147	14.0206
Maximum	74.74	121.46
Minimum	0.01	-24.92
Skewness	-0.955627	0.279215
Kurtosis	5.744057	4.388169

Source: Own elaboration with data from ENTSO-E.

It is important to mention that all the figures and tables presented are of own elaboration with data from the OMIE and ENTSO-E website with the statistical package Stata.

4.2 Methodology

For this research, the methodology of Ciarreta, Espinosa and Pizarro-Irizar (2014) has been taken into account. We use data for the day-ahead market and measure the Marginal System Price (MSP) and the Marginal Tradable Volume (MTV) of the spot market. We simulate different scenarios and we measure the price differences between them, driven by the merit order effect.

To build the algorithm we take into account three equations:

$$q_{min}(p_i) = min\{q_{ask}(p_i), q_{bid}(p_i)\} \tag{1}$$

$$q_{traded} = \max_{p_i}\{q_{min}(p_i)\} \tag{2}$$

$$p_{traded} = q_{bid}^{-1}(q_{traded}) \tag{3}$$

Where:

- $q_{ask}(p_i)$: Aggregate volume of ask orders at prices (p_i).

- $q_{bid}(p_i)$: Aggregate volume of offers at prices (p_i).

Equation (1) expresses the fact that for each price the quantity traded would be the short side of the market. Equation (2) computes the quantity traded (q_{traded}) as the maximum of the quantities obtained in Equation (1). For its part, Equation (3) find the market clearing price or market price (MSP) according to the market rules. Quantities are expressed in MWh and prices in euros per MWh.

Furthermore, Ciarreta, Espinosa and Pizarro-Irizar's (2017) create a synthetic supply curve structure based on a reference year including changes in some of the technologies. Hence, we proceed based on the algorithm of Ciarreta, Espinosa and Pizarro-Irizar's (2014) and Ciarreta, Espinosa and Pizarro-Irizar's (2017) synthetic bidding structure.

For the elaboration of the scenarios and the analysis of the effect of these on the electricity prices in Spain, the data for 2019 have been modified in three instances, first one, modifying the production of nuclear energy in France (4.2.1), second one, modifying the interconnection capacity between France and Spain (4.2.2) and finally, modifying the production of coal and renewable energies (4.2.3).

4.2.1 Nuclear energy in France

In the first instance, for the changes in the production of nuclear energy in France, have been taken into account the requirements of the "Energy and climate" law of France, which plans to reduce the participation of nuclear energy to 50% by 2035. For this purpose, a "Baseline" scenario has been prepared, which reduces the production of French nuclear energy to 50% in line with its plan. However, assuming that France cannot achieve this goal, a "pessimistic" scenario is prepared in which France only reduces its nuclear energy production by 25%. On the other hand, assuming that France will not only meet its target for 2035, but will also reduce 100% of nuclear energy in France, the "optimistic" scenario is created.

As the production of nuclear energy in France corresponds to 70.6% of electricity production, the participation of nuclear energy over the total electricity exports to Spain is considered to be proportional. Once the nuclear energy reduction is applied, the MSP and MTV are recalculated and compared to the current scenario or Benchmark to measure the effect of the reduction of nuclear energy.

4.2.2 Spain interconnection capacity

In the second instance, taking into account that PNIEC 2021-2030 aims to increase the interconnection capacity between Spain and France to 8,000 MW, the original bases are taken, the interconnection capacity is increased from 2,800 MW to 8,000 MW and the MSP and MTV are recalculated to compare with the Benchmark.

In accordance with the above, three other scenarios are proposed resulting from modifying in the original database the maximum interconnection capacity and the reduction of nuclear energy in France as indicated in Section 4.2.1.

4.2.3 Production of coal and renewable energy

In the third instance, the production of coal has been reduced and some renewable technologies have been increased according to the PNIEC 2021-2030, as it is shown in the Table 2. Have been chosen to be modified wind energy, photovoltaic solar energy and thermoelectric solar energy because they are considered to be the only intermittent renewable energies and those that most affect price volatility. Also, these technologies are the ones that currently have the largest participation and those that according to the PNIEC 2021-2030 will have the most changes.

Also at the time of making changes in technology has been taken into account the capacity factor, for wind energy is usually 10-40%, for photovoltaic solar energy is 10-30% and the thermoelectric solar energy can operate with a very high capacity factor. Once it has increased renewable energy, taking into account its capacity factor and the reduction of coal to zero, has been recalculated MSP and MTV to compare with the Benchmark.

Table 2: Evolution of the installed power of electric energy (MW).

Technologies	2020	2030
Wind Energy	28,033	50,333
Photovoltaic Solar Energy	9,071	39,181
Thermoelectric Solar Energy	2,303	7,303
Coal	7,897	0

Source: Own elaboration with data from PNIEC 2021-2030.

Continuing with the analysis of the effect of the reduction of coal and the increase of renewable energies, this scenario is combined with the scenarios in which nuclear energy is modified 4.2.1, the MSP and MTV are recalculated to be compared with the Benchmark or base scenario.

Continuing the same analysis, the changes made to coal and renewable energy, taking into account their capacity factor, is combined with the increase of the interconnection capacity to the maximum as mentioned in 4.2.2, the MSP and MTV are recalculated to be compared with the Benchmark or base scenario.

Finally, the previous scenario which considers changes in coal, changes in renewable energy and interconnection capacity are combined with scenarios that modify nuclear energy in France (4.2.1) has also been recalculated the MSP and the MTV to be compared with the Benchmark, and these last three can be considered as the most realistic scenarios, since they take into account both what is established by the laws in France, and what is established in the PNIEC 2021-2030 in Spain.

4.3 Scenarios

First of all, we present a current scenario or Benchmark, which does not consider the objectives established either in the PNIEC 2021- 2030 or the other laws about the increase of interconnection and renewable energy, and the reduction of coal and nuclear energy. It reflects the actual bidding structure (no changes at all). We will consider this scenario to compare the other counterfactual scenarios, where we update the interconnection size between Spain and France, the nuclear capacity in France or the capacity of the different Spanish technologies.

To analyze the effect that the phase-out of French nuclear energy will have on the Spanish electricity prices, the following scenarios with synthetic bids have been elaborated, they can also be found in Table 3.

- Scenario 1: Optimistic scenario with a 100% reduction in nuclear energy, keeping the other variables constant.
- Scenario 2: Baseline scenario with a 50% reduction in nuclear energy, considering that France plans to reduce the participation of nuclear energy to 50% by 2035, keeping the other variables constant.
- Scenario 3: Pessimistic scenario with just a 25% reduction in nuclear energy, keeping the other variables constant.
- Scenario 4: Scenario of maximum interconnection capacity, taking into account that the PNIEC 2021-2030 aims to increase the interconnection capacity between Spain and France to 8,000 MW, keeping the other variables constant.
- Scenario 5: Optimistic scenario with a 100% reduction in nuclear energy and maximum interconnection capacity.
- Scenario 6: Baseline scenario with a 50% reduction in nuclear energy and maximum interconnection capacity.
- Scenario 7: Pessimistic scenario with just a 25% reduction in nuclear energy and maximum interconnection capacity.
- Scenario 8: Scenario with a reduction of coal to 100% and an increase in renewable energies, taking into account the objectives established in the PNIEC 2021-2030, keeping the other variables constant.
- Scenario 9: Optimistic scenario with a 100% reduction in nuclear energy, a reduction of coal to 100% and an increase in renewable energies.

- Scenario 10: Baseline scenario with a 50% reduction in nuclear energy, a reduction of coal to 100% and an increase in renewable energies.

- Scenario 11: Pessimistic scenario with just a 25% reduction in nuclear energy, a reduction of coal to 100% and an increase in renewable energies.

- Scenario 12: Scenario of maximum interconnection capacity and a reduction of coal to 100% and an increase in renewable energies, keeping the other variables constant.

- Scenario 13: Optimistic scenario with a 100% reduction in nuclear energy, with maximum interconnection capacity, a reduction of coal to 100% and an increase in renewable energies.

- Scenario 14: Baseline scenario with a 50% reduction in nuclear energy, with maximum interconnection capacity, a reduction of coal to 100% and an increase in renewable energies.

- Scenario 15: Pessimistic scenario with just a 25% reduction in nuclear energy, with maximum interconnection capacity, a reduction of coal to 100% and an increase in renewable energies.

Table 3: Benchmark and scenarios prepared with synthetic bids.

Scenarios	Changes in nuclear energy			Maximum Interconnection Capacity	Changes in Coal and Renewable Energy
	Optimistic 100%	Baseline 50%	Pessimistic 25%		
Benchmark					
Scenario 1	X				
Scenario 2		X			
Scenario 3			X		
Scenario 4				X	
Scenario 5	X			X	
Scenario 6		X		X	
Scenario 7			X	X	
Scenario 8					X
Scenario 9	X				X
Scenario 10		X			X
Scenario 11			X		X
Scenario 12				X	X
Scenario 13	X			X	X
Scenario 14		X		X	X
Scenario 15			X	X	X

Source: Own elaboration.

The results ex-ante obtained with these synthetic bids, that consider different market situations, are explained and analyzed in the next section.

5 Results and Discussion

In this section we describe the results obtained in each scenario (5.1), a brief wefare analysis is performed (5.2) and through the Kruskal-Wallis equality-of-populations rank test we seek to strengthen the results. (5.3).

5.1 Scenarios with synthetic bids

In this section different scenarios are presented with ex-ante results assuming changes in nuclear energy and the combination of these with changes in interconnection capacity, changes in coal and changes in renewable energy, since the PNIEC 2021-2030 aims to to increase the interconnection capacity between Spain and France and the "Energy and Climate" law of France plans to reduce the participation of nuclear energy over the total energy production.

Changes in nuclear energies have always taken into account three possible scenarios, an optimistic scenario with the reduction of 100% in nuclear energies, a baseline scenario with the reduction of 50% in nuclear energies and a pessimistic scenario with the reduction of only 25% of nuclear energy.

To carry out the analysis of the first scenarios modifying the nuclear energy produced by France, Table 4 shows the results of the weighted average price (in euros) and the monthly sum of the Benchmark (in TWh) or current scenario, compared to the first three scenarios, optimistic scenario, baseline scenario and pessimistic scenario. It can be seen also the annual weighted average price and the annual sum for each scenario.

The results show that the reduction of nuclear energy in France, increase the prices and decrease the quantities. Larger reduction in nuclear energy, increase the price, in other words, the optimistic scenario is the one with the highest weighted average price. Because, as expected, at a lower production of energy, prices would tend to increase and as production decreases and this decrease is not followed by another policy to counteract the effect, prices will be higher and higher.

On the other hand considering only the quantity and not the price, larger reduction in nuclear energy, lower the quantities, in other words, the optimistic scenario is the one with the smallest quantities. This effect is expected because a lower production of nuclear energy is not followed by another policy that incentivizes the maintenance of the same negotiated quantities.

To the previous scenarios in which a policy of nuclear energy reduction is carried out in France, a policy of increasing the interconnection capacity in Spain to the maximum is now applied and Table 5 shows the weighted average price (in euros) and the monthly sum (in TWh) for Benchmark and scenarios with changes in interconnection and nuclear energy (optimistic, baseline and pessimistic). It can be seen also the annual weighted average price and the annual sum for each scenario.

Table 4: Weighted Average Price (euros) and Monthly Sum (TWh) for Benchmark and scenarios with changes in nuclear energy.

Date	Benchmark		Scenarios with changes in nuclear energy					
			Optimistic		Baseline		Pessimistic	
	Euros	TWh	Euros	TWh	Euros	TWh	Euros	TWh
jan-19	15.06	22.54	15.16	22.00	15.10	22.28	15.11	22.41
feb-19	26.66	22.43	25.55	21.98	26.14	22.21	26.38	22.33
mar-19	33.62	20.42	35.60	20.00	34.63	20.21	34.13	20.31
apr-19	25.49	19.94	27.41	19.63	26.44	19.79	25.97	19.87
may-19	31.52	21.03	33.63	20.71	32.64	20.87	32.07	20.95
jun-19	39.56	21.70	41.25	21.46	40.41	21.58	39.97	21.64
jul-19	30.59	19.65	32.43	19.44	31.51	19.54	31.09	19.60
aug-19	23.54	20.05	27.23	19.72	25.28	19.88	24.43	19.97
sep-19	22.14	19.57	26.37	19.27	24.22	19.42	23.23	19.49
oct-19	21.26	21.10	27.89	20.54	24.66	20.83	23.03	20.96
nov-19	31.35	19.89	35.57	19.36	33.47	19.62	32.42	19.76
dec-19	43.32	23.69	43.91	23.23	43.78	23.46	43.55	23.57
2019	28.80	252.02	31.07	247.35	29.96	249.70	29.39	250.86

Source: Own elaboration with data from OMIE.

As can be seen, the Benchmark is always the same, because it corresponds to the current scenario. The following scenario corresponds to the maximum capacity, which responds to the objective of increasing the interconnection capacity between Spain and France to 8,000 MW. The scenarios with changes in nuclear energy correspond to the increase in interconnection to its maximum capacity and the decrease in nuclear energy in an optimistic, baseline and pessimistic scenario.

The table shows that with an increase in the interconnection capacity to the maximum, prices decrease drastically, but if this scenario is combined with the reduction of nuclear energy, prices increase. As nuclear energies are reduced, the weighted average price increases. Moreover, in the optimistic scenario, where interconnection is increased to the maximum and 100% of nuclear energies are reduced, the price is higher than the Benchmark.

These results are expected because, if the policy of reduction of nuclear energy in France is accompanied by another policy of increasing interconnection capacity to the maximum , the increase in prices caused by a lower amount of energy is balanced by the increase in interconnection, which makes prices fall even more than the current scenario or benchmark.

On the other hand, if the quantities are observed, when increasing the interconnection capacity to the maximum, the quantity increases, but as the nuclear energy decreases, the quantities also decrease, in the case of the optimistic scenario, the quantity reaches to be lower than the Benchmark.

If we compare Tables 4 and 5, where the difference lies in the change in the interconnection

Table 5: Weighted Average Price (euros) and Monthly Sum (TWh) for Benchmark and scenarios with changes in interconnection and nuclear energy.

Date	Benchmark		Maximum Capacity		Scenarios with changes in interconnection and nuclear energy					
					Optimistic		Baseline		Pessimistic	
	Euros	TWh	Euros	TWh	Euros	TWh	Euros	TWh	Euros	TWh
jan-19	15.06	22.54	16.52	23.82	15.09	22.43	15.35	23.15	15.91	23.49
feb-19	26.66	22.43	29.58	23.61	26.43	22.34	28.04	22.97	28.85	23.29
mar-19	33.62	20.42	27.53	21.62	34.05	20.33	30.98	20.98	29.35	21.31
apr-19	25.49	19.94	20.49	20.72	25.89	19.88	23.10	20.31	21.78	20.52
may-19	31.52	21.03	24.72	21.81	31.98	20.96	28.51	21.41	26.75	21.61
jun-19	39.56	21.70	35.00	22.40	39.90	21.65	37.49	22.01	36.27	22.20
jul-19	30.59	19.65	23.91	20.27	30.99	19.61	27.88	19.93	26.01	20.10
aug-19	23.54	20.05	15.26	20.91	24.25	19.98	19.43	20.46	17.29	20.70
sep-19	22.14	19.57	11.69	20.34	23.01	19.51	16.77	19.94	14.20	20.14
oct-19	21.26	21.10	6.87	22.32	22.75	20.98	13.51	21.70	9.79	22.02
nov-19	31.35	19.89	17.46	21.17	32.24	19.78	25.17	20.51	21.36	20.85
dec-19	43.32	23.69	39.51	24.87	43.51	23.59	41.50	24.23	40.40	24.55
2019	28.80	252.02	22.67	263.87	29.29	251.06	25.84	257.61	24.24	260.78

Source: Own elaboration with data from OMIE.

capacity, we can see that in the optimistic, baseline and pessimistic scenario, the weighted average prices are lower when the interconnection is modified, while the quantities increase, the biggest difference is observed in the pessimistic scenario.

In line with the scenario analysis, we leave aside the interconnection and take into account the reduction of coal and the increase of other renewable energies. Table 6 shows the weighted average price (in euros) and monthly sum (in TWh) for Benchmark and scenarios with changes in coal, renewable energy and nuclear energy (optimistic, baseline and pessimistic). It can be seen also the annual weighted average price and the annual sum for each scenario.

The first scenario compared to the Benchmark corresponds to a 100% reduction of coal and an increase in the production of renewable energy, taking into account what is established in the PNIEC 2021-2030, it can be seen that, in this scenario, the weighted average price decreases, however, as nuclear energies are reduced, the price increases again, but does not exceed the weighted average price of the current scenario or Benchmark.

These results are expected because, after a reduction in nuclear energy production and an increase in prices, the elimination of coal and the increase in renewable energy production could be a policy option to counteract the increase in prices.

On the quantity side, with the reduction of coal and the increase in renewable energies, the quantity increases. But, as the nuclear energies are reduced, the quantities decrease again, but they are not lower than the Benchmark. These results are also expected because as the production of renewable energy increases the quantity increases and as the production of nuclear energy decreases, the quantity decreases.

Table 6: Weighted Average Price (euros) and Monthly Sum (TWh) for Benchmark and scenarios with changes in coal, renewable energy and nuclear energy.

Date	Benchmark		Changes in coal and renewable energy		Scenarios with changes in coal, renewable energy and nuclear energy					
					Optimistic		Baseline		Pessimistic	
	Euros	TWh	Euros	TWh	Euros	TWh	Euros	TWh	Euros	TWh
jan-19	15.06	22.54	10.95	23.20	10.90	22.70	10.90	22.96	10.91	23.08
feb-19	26.66	22.43	14.24	23.78	13.36	23.27	13.69	23.52	13.96	23.65
mar-19	33.62	20.42	29.98	20.78	32.02	20.37	31.02	20.58	30.54	20.68
apr-19	25.49	19.94	23.37	20.14	24.94	19.86	24.17	20.00	23.77	20.07
may-19	31.52	21.03	31.61	20.90	33.64	20.58	32.67	20.74	32.17	20.82
jun-19	39.56	21.70	39.01	21.69	40.71	21.47	39.83	21.58	39.41	21.63
jul-19	30.59	19.65	29.29	19.67	31.17	19.44	30.24	19.56	29.75	19.62
aug-19	23.54	20.05	20.17	20.39	23.10	20.10	21.58	20.24	20.89	20.31
sep-19	22.14	19.57	17.46	20.40	20.76	19.98	19.10	20.19	18.25	20.29
oct-19	21.26	21.10	17.26	21.51	22.95	20.96	20.07	21.24	18.66	21.38
nov-19	31.35	19.89	30.33	19.87	34.82	19.36	32.55	19.61	31.41	19.74
dec-19	43.32	23.69	29.66	24.59	30.79	24.04	30.26	24.32	30.02	24.45
2019	28.80	252.02	24.29	256.92	26.39	252.15	25.32	254.53	24.81	255.73

Source: Own elaboration with data from OMIE.

If Tables 4 and 6 are compared, where the difference between these lies in changes in coal and renewable energies, it can be seen that the weighted average price of the optimistic, baseline and pessimistic scenario are lower with the change in coal and renewable energies, while the quantities are higher, however, were not observed variations as great as when Table 4 was compared with Table 5, where the difference lay in the interconnection capacity.

Now, the different scenarios analyzed in Table 6 will be combined with the increase in interconnection capacity. Table 7 shows the weighted average price (in euros) and monthly sum (in TWh) for Benchmark and scenarios with changes in coal, renewable energy, interconnections and nuclear energy (optimistic, baseline and pessimistic scenario). It can be seen also the annual weighted average price and the annual sum for each scenario.

It can be seen that the first scenario compared to the Benchmark, in which 100% of coal is reduced, the production of renewable energy is increased, as established in the PNIEC 2021-2030, and the interconnection capacity is increased by maximum, the weighted average price is much lower. However, as nuclear power is decreased in the following scenarios, the price increases again, but they do not reach the weighted average price of the Benchmark.

The results are as expected, since a reduction in nuclear energy in France would increase prices in Spain, however, with the increase in renewable energy production, the increase in prices would be compensated.

If the quantities are taken into account, the first scenario drastically increases the quantity, but as the nuclear energy is reduced the quantities tend to decrease, however in the optimistic scenario, where 100% of the nuclear energies are reduced, the amount is not less than the Benchmark. This is also the expected result because as renewable energy production increases, the quantity will increase, and as nuclear energy production decreases, the quantity will decrease.

Table 7: Weighted Average Price (euros) and Monthly Sum (TWh) for Benchmark and scenarios with changes in coal, renewable energy, interconnections and nuclear energy.

Date	Benchmark		Changes in coal, renewable energy and interconnections		Scenarios with changes in coal, renewable energy, interconnections and nuclear energy					
					Optimistic		Baseline		Pessimistic	
	Euros	TWh	Euros	TWh	Euros	TWh	Euros	TWh	Euros	TWh
jan-19	15.06	22.54	11.63	24.43	10.90	23.10	10.99	23.77	11.25	24.10
feb-19	26.66	22.43	17.78	25.13	14.02	23.67	15.70	24.40	16.73	24.77
mar-19	33.62	20.42	24.43	21.88	30.45	20.70	27.48	21.30	25.98	21.60
apr-19	25.49	19.94	18.90	20.96	23.72	20.08	21.36	20.51	20.08	20.73
may-19	31.52	21.03	25.45	21.71	32.08	20.83	28.87	21.29	27.14	21.50
jun-19	39.56	21.70	34.56	22.37	39.34	21.64	36.92	22.00	35.80	22.18
jul-19	30.59	19.65	23.50	20.28	29.66	19.63	26.81	19.95	25.16	20.12
aug-19	23.54	20.05	13.49	21.25	20.76	20.33	16.98	20.76	15.23	21.00
sep-19	22.14	19.57	8.99	21.46	18.14	20.31	13.22	20.87	10.92	21.17
oct-19	21.26	21.10	5.33	23.03	18.46	21.40	11.05	22.17	8.00	22.58
nov-19	31.35	19.89	16.99	21.34	31.23	19.76	24.55	20.54	21.00	20.94
dec-19	43.32	23.69	27.87	25.99	29.91	24.48	28.57	25.24	28.13	25.61
2019	28.80	252.02	19.10	269.85	24.72	255.94	21.80	262.81	20.42	266.31

Source: Own elaboration with data from OMIE.

The scenarios presented in this section show ex-ante results that could occur when interconnection capacity is modified, coal is decreased, renewable energies are increased and nuclear energies from France are gradually reduced.

5.2 Cost- Benefit Analysis

Continuing the analysis of the proposed scenarios, Table 8 represents the monthly and annual differences of the product of price and quantity with respect to the Benchmark (in millions of euros), it allows to obtain an overview of all the scenarios with respect to whether the changes introduced in each scenario represent income or not.

Making a comparison between scenarios in which nuclear energy has not been modified, it can be seen that the best scenario would be the one that presents a reduction in coal, and an increase in renewable energy and interconnections (Scenario 12).

Analyzing the scenarios in which nuclear energy is modified, it can be seen that the worst scenarios are those in which nuclear energy is reduced to 100%, that is, the optimistic scenario, because they are the ones that present the lowest results. Comparing the optimistic scenarios the worst is the one that reduces 100% of nuclear energy in France (Scenario 1).

Making a comparison between the pessimistic scenarios, the best pessimistic scenario is the one that the 25% reduction in nuclear energy in France is accompanied by a maximum increase in interconnection capacity and an increase of renewable energy and reduction of coal.

For its part, comparing the baseline scenarios, the best baseline scenario is the one that in addition to the 50% reduction in nuclear energy in France, interconnection is increased to the maximum capacity and those are accompanied by an increase of renewable energy and reduction of coal.

The differences that can be observed in Table 8 clearly show which are the most convenient scenarios in terms of price and quantity, in general, the reduction in nuclear energy represents a reduction in income, and if they are totally eliminated from the system it leads to negative results, however, this reaction is counteracted with the increase in interconnection capacity, which in the proposed scenarios this increase is at its maximum capacity.

Table 8: Monthly and annual differences of the product of price and quantity with respect to the Benchmark (in millions of euros).

Date	Scenarios with changes in nuclear energy			Max. Capac.	Scenarios with changes in interconnection and nuclear energy			Changes in coal and renewable energy	Scenarios with changes in coal, renewable energy and nuclear energy			Changes in coal, renewable energy and inter-connec-tions	Scenarios with changes in coal, renewable energy, interconnections and nuclear energy		
	Opt.	Bas.	Pes.		Opt.	Bas.	Pes.		Opt.	Bas.	Pes.		Opt.	Bas.	Pes.
jan-19	5.82	2.95	0.77	-53.96	1.02	-15.99	-34.35	85.48	91.95	89.16	87.53	55.39	87.67	78.19	68.33
feb-19	36.42	17.61	9.20	-100.08	7.62	-45.94	-73.67	259.73	287.32	276.26	267.98	151.42	266.43	215.04	183.93
mar-19	-25.40	-13.21	-6.71	91.47	-5.74	36.66	61.03	63.54	34.30	48.29	55.20	152.03	56.48	101.44	125.39
apr-19	-29.58	-14.81	-7.49	83.92	-6.38	39.15	61.56	37.64	13.00	24.91	31.30	112.27	31.98	70.42	92.15
may-19	-33.46	-18.16	-8.97	123.73	-7.36	52.71	84.81	2.26	-29.41	-14.80	-6.87	110.30	-5.46	48.42	79.23
jun-19	-27.14	-13.72	-6.65	74.49	-5.53	33.20	53.19	12.07	-15.55	-0.95	5.81	85.13	6.90	46.15	64.24
jul-19	-29.15	-14.63	-7.99	116.53	-6.27	45.64	78.55	25.12	-4.78	9.82	17.62	124.54	19.10	66.38	95.19
aug-19	-64.91	-30.59	-15.66	152.93	-12.51	74.51	114.23	60.77	7.81	35.16	47.64	185.39	50.08	119.48	152.21
sept-19	-74.75	-37.07	-19.43	195.54	-15.44	98.91	147.21	77.29	18.56	47.72	63.03	240.46	65.01	157.33	202.14
oct-19	-124.31	-65.10	-34.26	295.08	-28.93	155.41	232.86	77.12	-32.65	22.16	49.57	325.65	53.47	203.51	267.78
nov-19	-65.24	-33.24	-17.09	253.84	-14.34	107.28	178.17	20.85	-50.76	-14.70	3.51	260.87	6.44	119.21	183.61
dec-19	5.97	-0.94	-0.41	43.47	-0.30	20.60	34.32	297.06	286.06	290.31	292.18	301.90	294.01	305.04	305.76
2019	-425.75	-220.90	-114.68	1,276.96	-94.15	602.14	937.91	1,018.92	605.85	813.33	914.52	2,105.35	932.12	1,530.61	1,819.96

Source: Own elaboration with data from OMIE.

5.3 Robustness test

Finalizing the price analysis, for the robustness of the results obtained in each scenario, has been performed a Kruskal-Wallis equality-of-populations rank test. It tested whether several independent samples come or not from the same population. It can be considered as a generalization of the Wilcoxon Rank Sum test.

The null hypothesis establishes that the distribution of the prices of the Benchmark and the distribution of the prices of each scenario are equal, while the alternative hypothesis establishes that the distribution of the prices of the Benchmark and the distribution of the prices of each scenario are not equal. The results obtained can be seen at Table 9 and the Kernel Density Estimation of Benchmark and each scenario can be seen in the Appendix.

In the case of the Benchmark with Scenario 5, the p-value is strictly greater than 0.01. Hence, we can't reject the null hypothesis and we conclude that the distribution of the prices of the Benchmark and the distribution of the prices of Scenario 5 are equal.

For the other scenarios, the p-value is strictly less than 0.01 so the null hypothesis is rejected and it can be concluded that the distribution of the prices of the Benchmark and the distribution of the prices of each scenario (except scenario 5) are not equal.

To identify the sign, for the Benchmark and Scenario 1, where the price distribution is not equal, the third column indicates that the cumulative distribution function of the Benchmark is below the cumulative distribution function of Scenario 1, and for this case the Benchmark is better.

On the other hand, for the Benchmark and Scenario 4, where the distribution of prices is also not equal, the third column indicates that the cumulative distribution function of the Benchmark is above the cumulative distribution function of Scenario 4, and for this case Scenario 4 is better.

From the results of this analysis, it can be concluded that scenario 5, corresponding to an optimistic scenario in which 100% of nuclear energy in France is reduced and interconnection capacity is increased to the maximum, is not statistically significant at the 1% significance level. In other words, taking nuclear energy reduction and capacity increase policies to the extreme would not be convenient scenarios.

Table 9: Kruskal-Wallis equality-of-populations rank test and cumulative distribution function results.

Benchmark with	Probability	Cumulative distribution function
Scenario 1	0.0001	$F_0(x) < F_1(x)$
Scenario 2	0.0001	$F_0(x) < F_2(x)$
Scenario 3	0.0055	$F_0(x) < F_3(x)$
Scenario 4	0.0001	$F_0(x) > F_4(x)$
Scenario 5	0.0224	$F_0(x) = F_5(x)$
Scenario 6	0.0001	$F_0(x) > F_6(x)$
Scenario 7	0.0001	$F_0(x) > F_7(x)$
Scenario 8	0.0001	$F_0(x) > F_8(x)$
Scenario 9	0.0001	$F_0(x) > F_9(x)$
Scenario 10	0.0001	$F_0(x) > F_{10}(x)$
Scenario 11	0.0001	$F_0(x) > F_{11}(x)$
Scenario 12	0.0001	$F_0(x) > F_{12}(x)$
Scenario 13	0.0001	$F_0(x) > F_{13}(x)$
Scenario 14	0.0001	$F_0(x) > F_{14}(x)$
Scenario 15	0.0001	$F_0(x) > F_{15}(x)$

Source: Own elaboration with data from OMIE.

6 Conclusions and Policy Implications

In this research, have been carried out fifteen possible scenarios, taking into account the "Energy and climate" law of France that plans to reduce 50% of the participation of nuclear energy on the total energy production and the objectives proposed by the PNIEC (2021 -2030) that aims to increase interconnection capacity, reduce coal production and increase renewable energy production.

The results in Section 5 show that the reduction of nuclear energy in France, increase the prices and decrease the quantities. The optimistic scenario is the one with the highest weighted average price and the smallest quantities.

With an increase in the interconnection capacity to the maximum, prices decrease drastically, but if this scenario is combined with the reduction of nuclear energy, prices increase. In the optimistic scenario the price is higher than the Benchmark. When increasing the interconnection capacity to the maximum, the quantity increases, but as the nuclear energy decreases, the quantities also decrease, in the case of the optimistic scenario, the quantity reaches to be lower than the Benchmark.

With a reduction of coal in a 100% and an increase in the production of renewable energy, the weighted average price decreases, however, as nuclear energies are reduced, the price increases again, but does not exceed the weighted average price of the current scenario or Benchmark. On the quantity side, with the reduction of coal and the increase in renewable energies, the quantity increases. But, as the nuclear energies are reduced, the quantities decrease again, but they are not lower than the Benchmark.

With a reduction of 100% of coal, the production of renewable energy is increased and the interconnection capacity is increased by maximum, the weighted average price is much lower. However, as nuclear power is decreased, the price increases again. If the quantities are taken into account, the quantity drastically increases, but as the nuclear energy is reduced the quantities tend to decrease, however in the optimistic scenario, where 100% of the nuclear energies are reduced, the amount is not less than the Benchmark.

Due to the aforementioned and the results obtained, as a policy implication it can be mentioned that it is important to support the reduction of coal and the increase in interconnection capacity and production of renewable energies as a way to counteract the increase in prices due to the phase-out of nuclear energy in France.

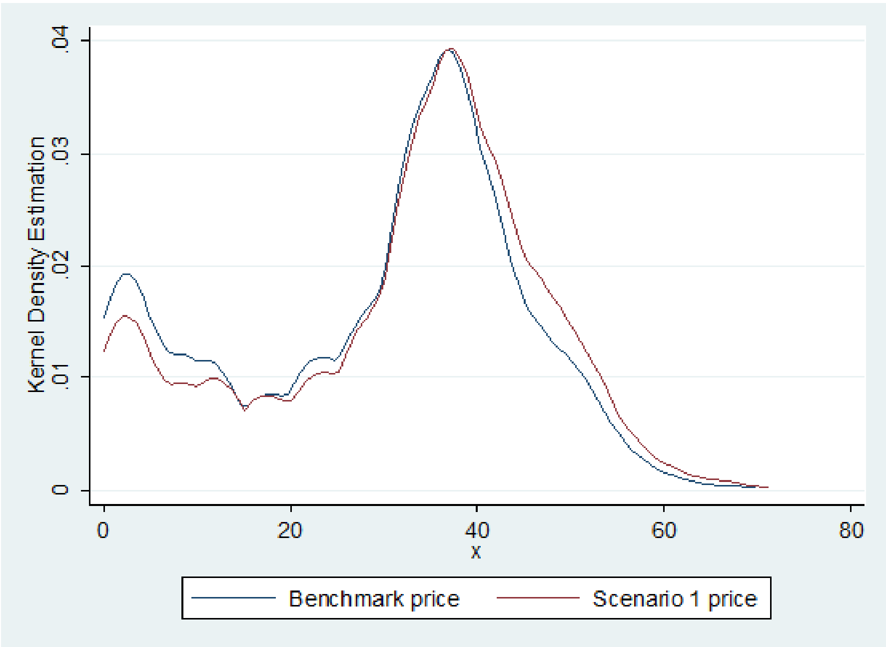
Taking into account the difference of the product of price and quantity with respect to the benchmark, the scenario with the best results is the one in which coal, renewable energies and interconnection capacity are modified (Scenario 12). And, the scenario with the worst results is the one that reduces 100% of nuclear energy in France (Scenario 1). From the best and the worst scenario, when comparing the price variation with the current or Benchmark scenario, we can conclude that the maximum price reduction is equal to 9.7 euros per MWh and the maximum price increment is 2.27 euros per MWh.

Thanks to Kruskal-Wallis equality-of-populations rank test results it has been possible to conclude that scenario 5, in which maximum interconnection capacity is combined with the elimination of a 100% of nuclear energy in France, is not statistically significant at the 1% significance level, so this paper does not recommend the implementation of policies that would take the elimination of nuclear energy in France to the extreme.

It can be mentioned that demand has not been modeled, this document has only concentrated on the supply side, but scenarios where demand is modified and the strategic behavior of the market participants (price endogeneity) could be included as further researches.

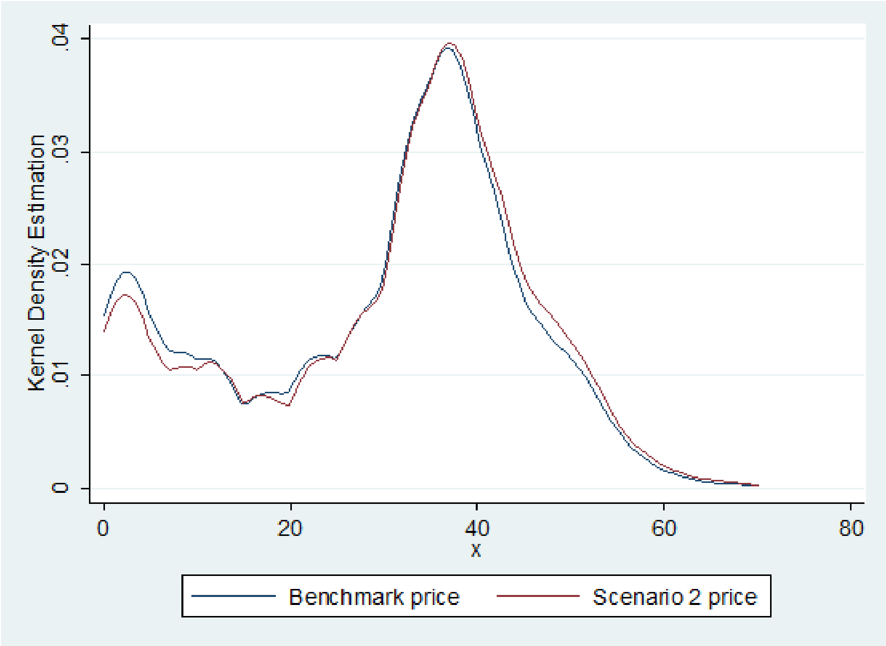
7 Appendix

Figure 8: Kernel Density Estimation of Benchmark and Scenario 1.



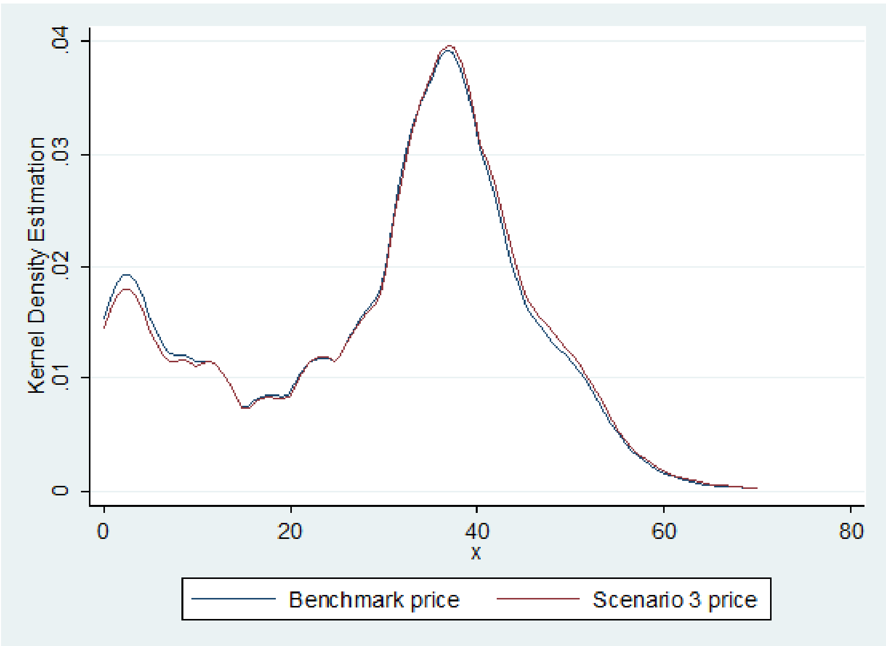
Source: Own elaboration with data from OMIE.

Figure 9: Kernel Density Estimation of Benchmark and Scenario 2.



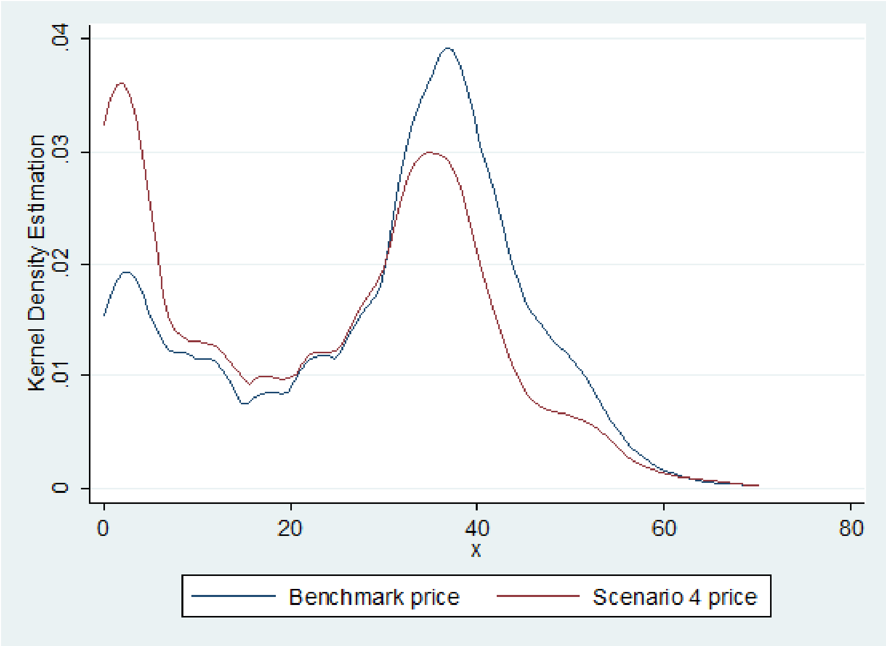
Source: Own elaboration with data from OMIE.

Figure 10: Kernel Density Estimation of Benchmark and Scenario 3.



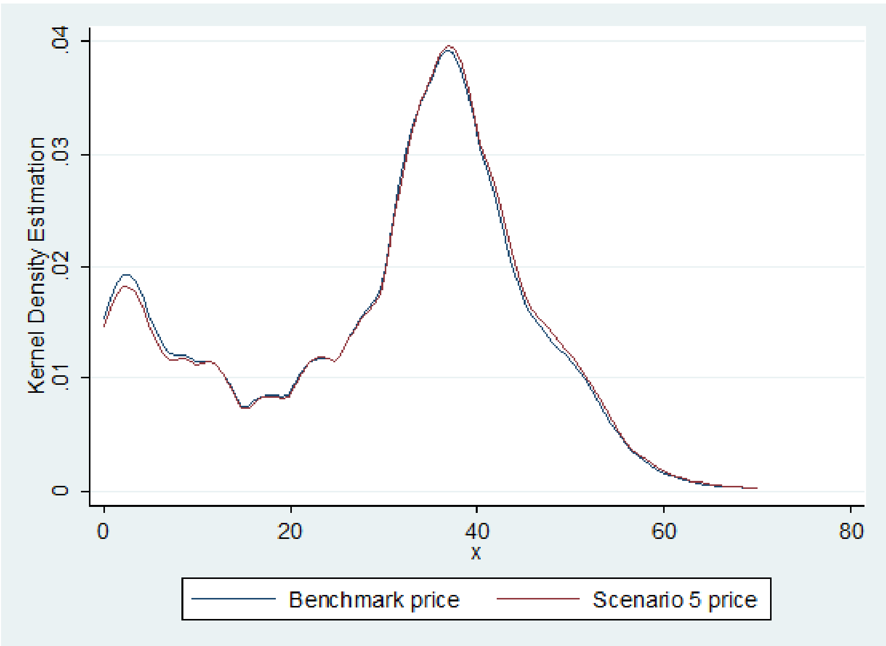
Source: Own elaboration with data from OMIE.

Figure 11: Kernel Density Estimation of Benchmark and Scenario 4.



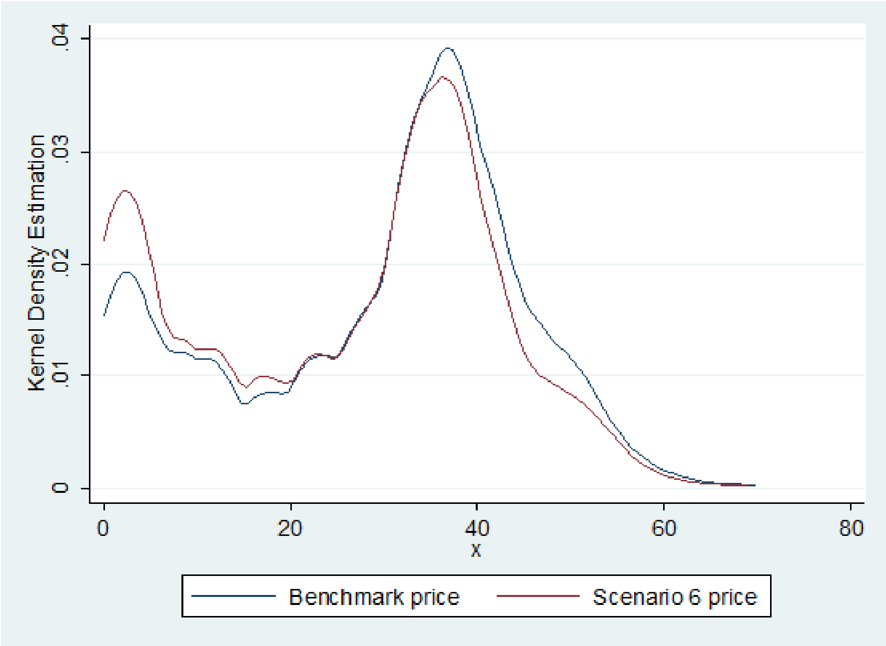
Source: Own elaboration with data from OMIE.

Figure 12: Kernel Density Estimation of Benchmark and Scenario 5.



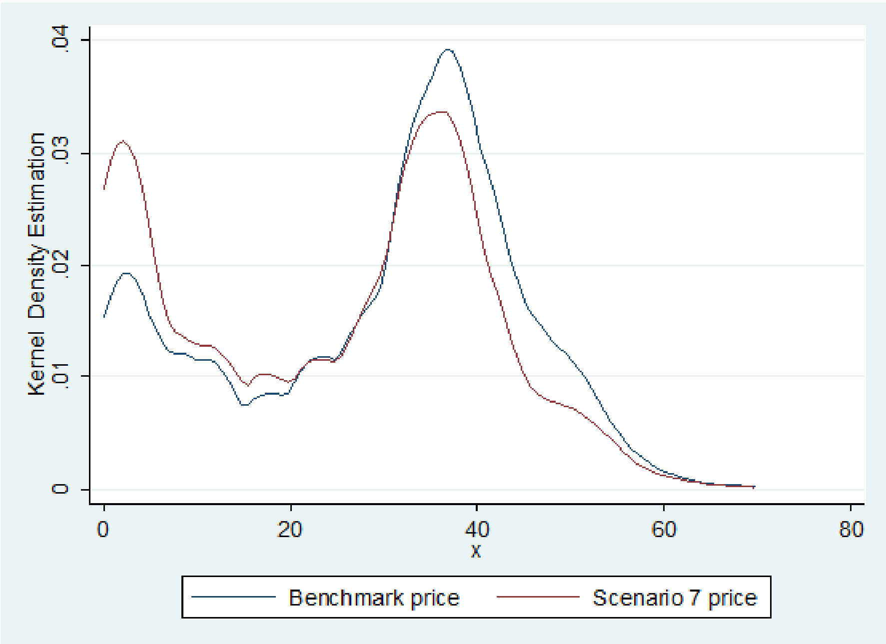
Source: Own elaboration with data from OMIE.

Figure 13: Kernel Density Estimation of Benchmark and Scenario 6.



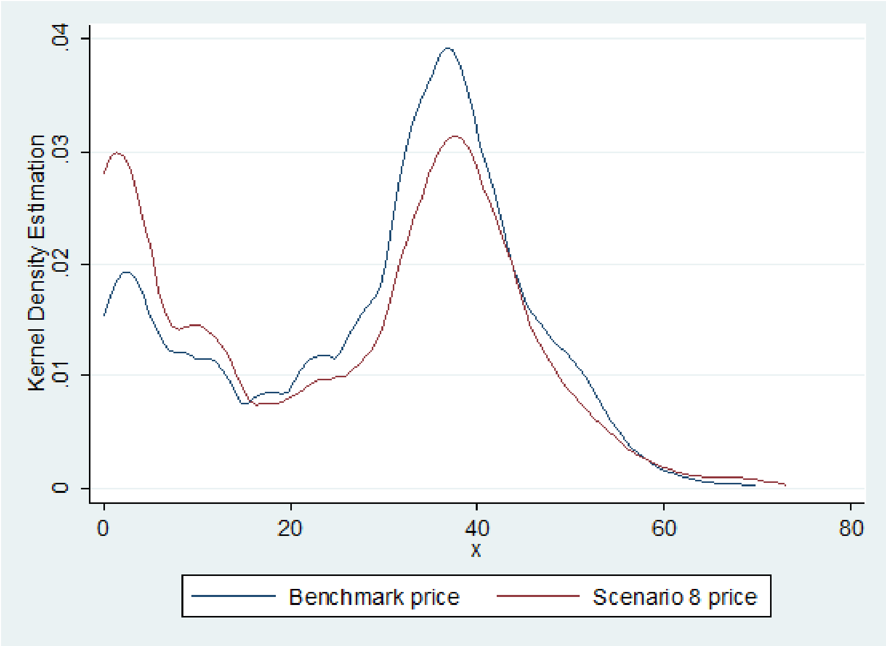
Source: Own elaboration with data from OMIE.

Figure 14: Kernel Density Estimation of Benchmark and Scenario 7.



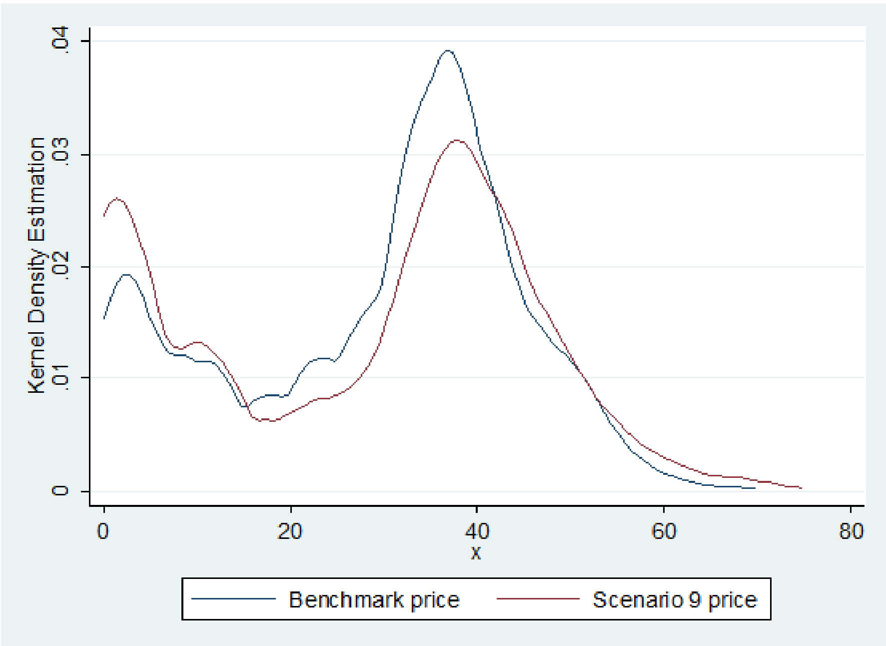
Source: Own elaboration with data from OMIE.

Figure 15: Kernel Density Estimation of Benchmark and Scenario 8.



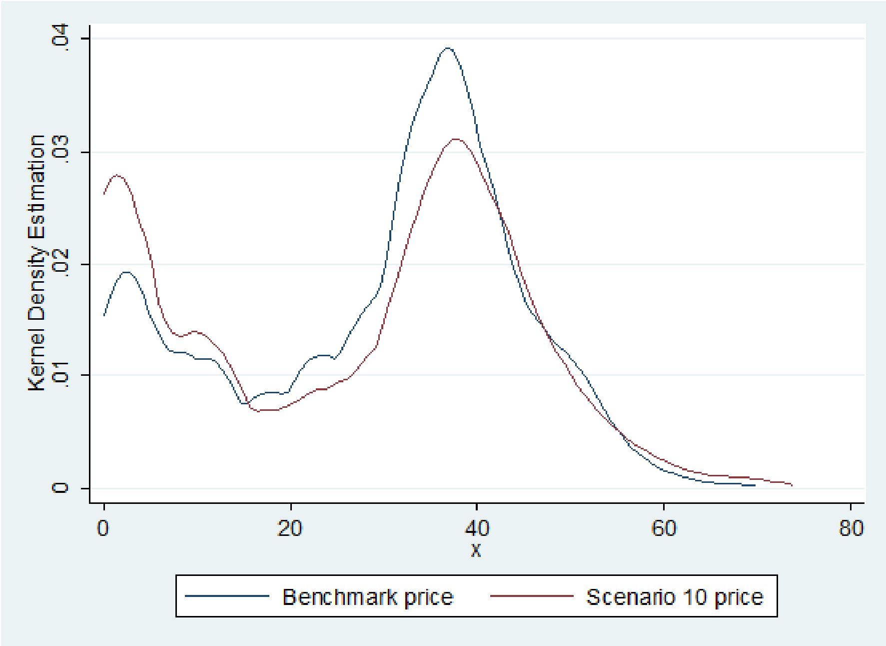
Source: Own elaboration with data from OMIE.

Figure 16: Kernel Density Estimation of Benchmark and Scenario 9.



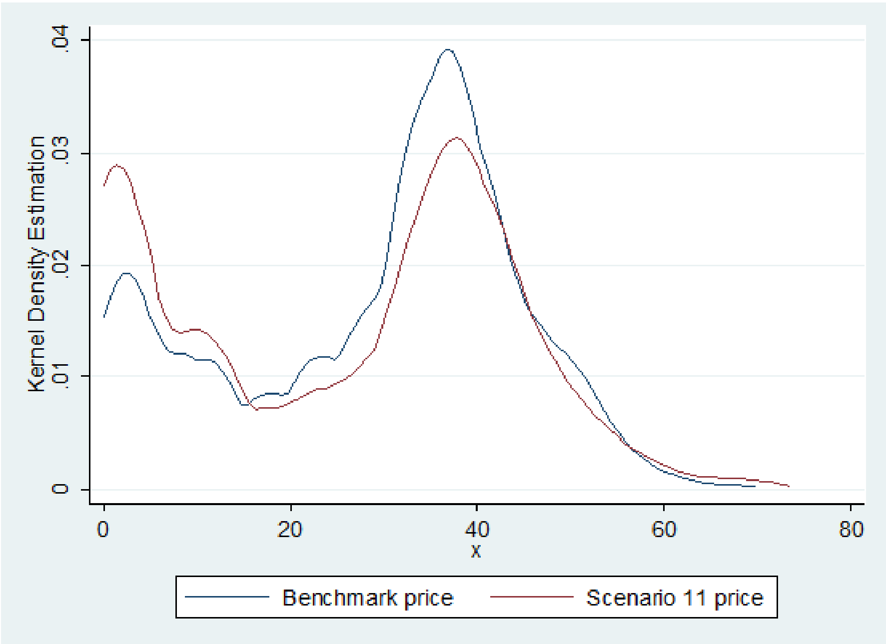
Source: Own elaboration with data from OMIE.

Figure 17: Kernel Density Estimation of Benchmark and Scenario 10.



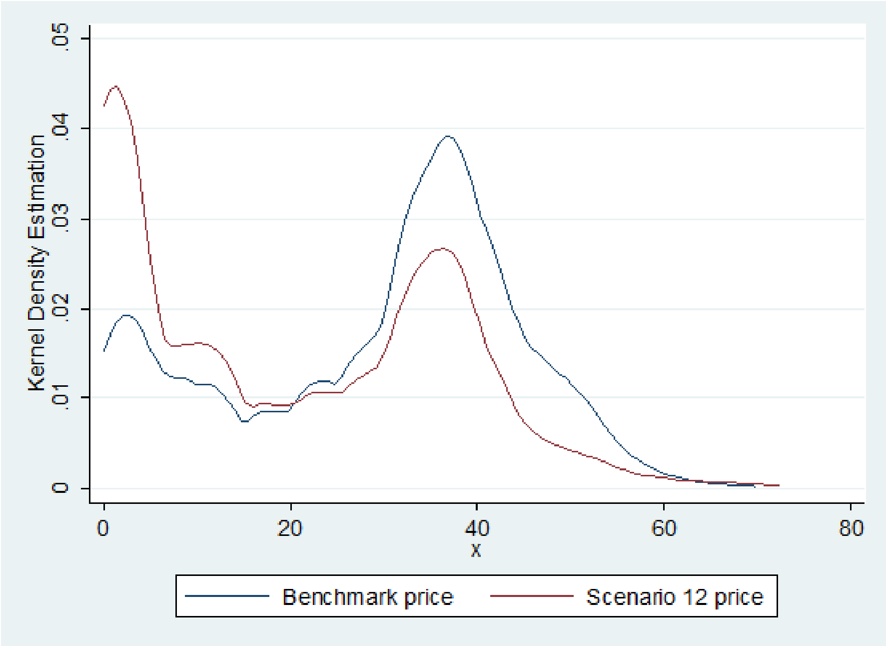
Source: Own elaboration with data from OMIE.

Figure 18: Kernel Density Estimation of Benchmark and Scenario 11.



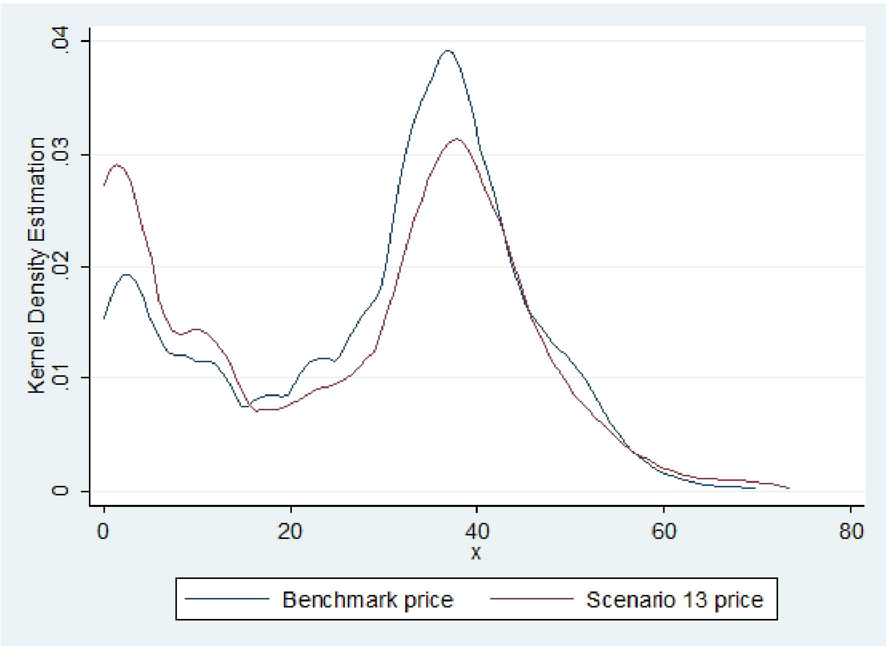
Source: Own elaboration with data from OMIE.

Figure 19: Kernel Density Estimation of Benchmark and Scenario 12.



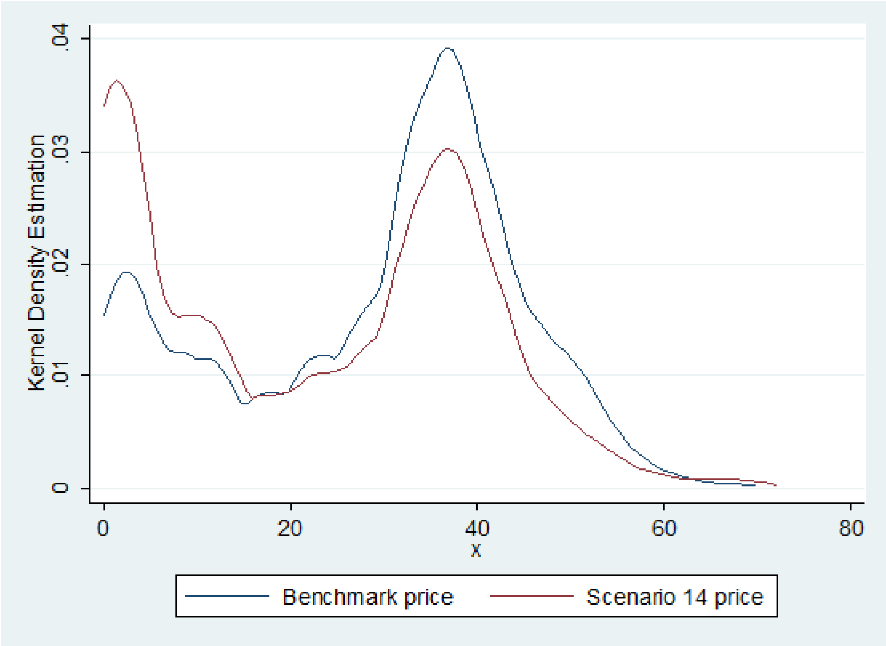
Source: Own elaboration with data from OMIE.

Figure 20: Kernel Density Estimation of Benchmark and Scenario 13.



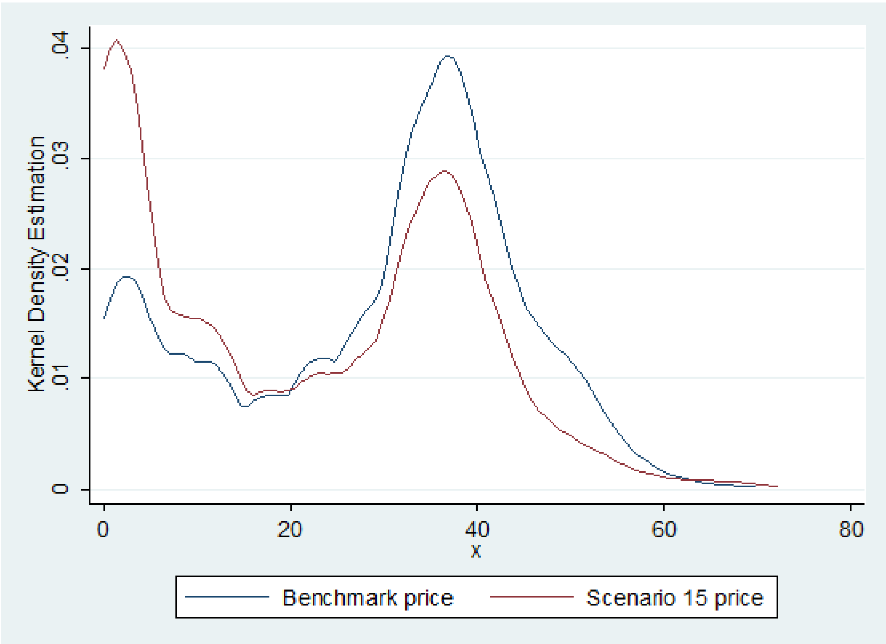
Source: Own elaboration with data from OMIE.

Figure 21: Kernel Density Estimation of Benchmark and Scenario 14.



Source: Own elaboration with data from OMIE.

Figure 22: Kernel Density Estimation of Benchmark and Scenario 15.



Source: Own elaboration with data from OMIE.

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