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Master’s Thesis

IMPACT OF RENEWABLE ENERGY INTEGRATION ON THE DAY-AHEAD MARKET IN 2025

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ABSTRACT

1. Introduction

We are currently experiencing a tremendous transformation of the electricity sector, where renewable generation technologies are becoming more and more important, with it becoming increasingly interesting to study their impact on the day-ahead market price. The lower cost of this type of technologies and the governments' efforts to achieve a total decarbonization of the energy sector are causing a very notable increase in the installed power of these technologies and, consequently, in their presence in the generation curve of our country. This was expected to result in decreased energy prices. However, due to the rapid increase in the cost of combined cycle power plant generation since 2021 due to rising gas prices, the opposite has occurred. The price of energy has skyrocketed in the past two years, reaching unprecedented highs.

This issue is of great significance because if renewable generation were to meet the entire demand of the system and leave combined cycle plants out of the market, it would result in a major change. It's likely that the price of energy would significantly decrease, as we have observed at certain times in the past year.

This thesis aims to analyze the situation of the electricity sector and its evolution, in order to study the impact that renewable technologies will have on the Spanish day-ahead market price in 2025 under different possible scenarios. This study is important not only for investors in the sector, but also for regulators, consumers and society as a whole, as it offers a vision of the future of energy prices and the economic consequences of the transition to a more sustainable and environmentally friendly energy system.

2. Methodology

The prediction model used for the thesis is called xPryce and the company that developed it is SIMULYDE. This model is formulated as an optimization problem, programmed in GAMS/CPLEX, and simulates the matching of the day-ahead MIBEL market and France.

A sensitivity study/analysis will be conducted to examine the influence of renewable energies on energy prices in 2025. In this type of analysis, different input parameters (wind power installed, solar PV power installed…) are systematically modified within

a specified interval, while keeping other parameters constant, to observe the corresponding changes in the output. By this, it is possible to understand how each parameter affects the system's behavior, in this case, the price of energy in the day ahead market. Being a study that aims to know how renewable technologies will affect the price of energy in the day-ahead market, it has been decided to study the scenarios where the installed capacity of solar and wind generation varies. These scenarios have been replicated in different cases where the price of gas has been modified.

The study will start by establishing a base case and a base scenario, in which the most likely parameters for the year 2025 will be defined. These parameters have been chosen based on the PNIEC, as well as on estimates made by Invesyde, the company that provided me with this price forecasting model.

Once the parameters that establish the base scenario and the base case are known, in order to analyze how renewables influence the price of the day-ahead energy market, simulations will be made of different cases in which the parameters that establish the price of gas in MIBGAS and TTF will be modified, and different scenarios in which the installed solar photovoltaic power and installed wind power will be modified, keeping others constant, such as, for example, demand or interconnection capacity. The input data for installed PV and wind power will be adjusted in intervals of 0.5 GW up to 3 GW above and below the values specified in the base case for each respective technology. In each scenario, the installed power will be adjusted both in year n (2025) and year n-1 (2024), aiming to thoroughly assess the influence these technologies exert on the market price. As for gas, it has been decided to study the cases in which the price rises in MIBGAS and TTF with respect to the expected: 1 €/MWh, 5 €/MWh and double, the latter replicating an unexpected geopolitical situation such as the war in Ukraine.

The types of analysis will be performed on a case-by-case basis:

- <u>Comparison of annual average day-ahead market prices</u> as a function of the installed power of solar photovoltaic and wind technologies using a two-dimensional matrix and a three-dimensional graph to be able to study the slopes formed by the points representing the annual average price of each scenario.

- <u>Comparison of the monthly prices</u> <u>of the most relevant cases</u>: A graph will be made where the average monthly day-ahead market prices of the most relevant scenarios will be superimposed.

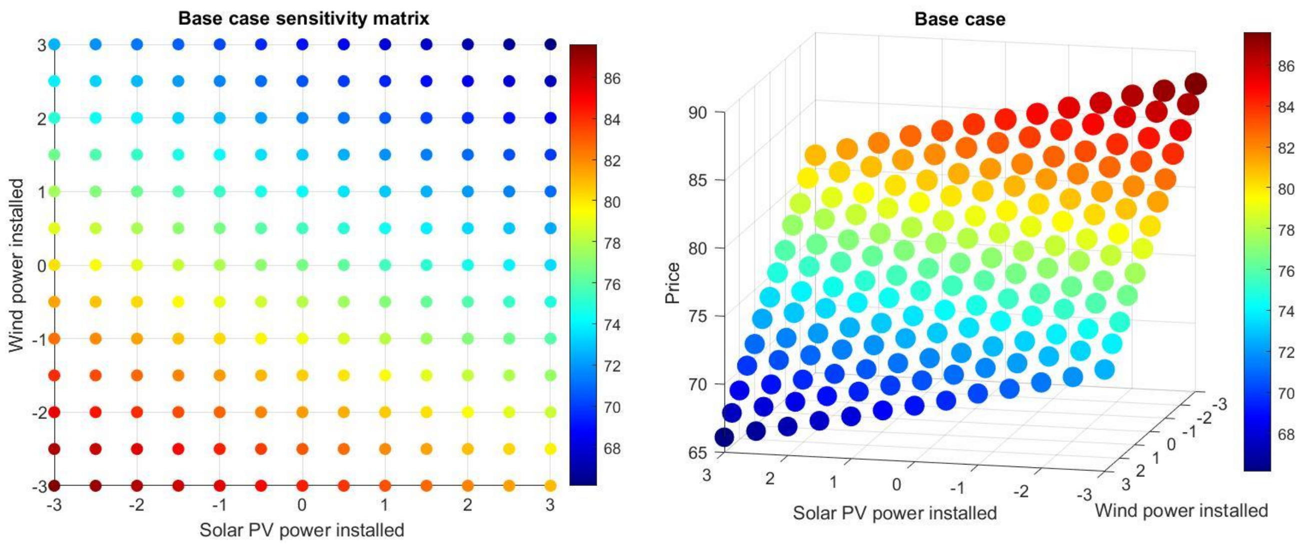
- <u>Capture price study</u>: In the same way that the annual prices of the different scenarios indicated were represented, the solar and wind capture prices will be represented to study the remuneration of these technologies.

- <u>Study of the economic viability of the different technologies</u>: With the calculated capture price, the remuneration expected for each technology will be calculated and compared with its LCOE respectively to check the viability of these installations according to the scenario.

3. Results

Once the simulations were carried out with the prediction model, MATLAB and Microsoft Excel were used to analyze and represent the results obtained in the best possible way.

The base case, where the gas price is the most expected for 2025, is the case that has been analyzed in greater detail, considering the scenarios mentioned in the methodology to obtain different results with which the analysis has been carried out. Probably the most relevant result of the thesis, since it shows how the increase of solar PV and wind power affect the day-ahead market price keeping all other variables constant, is the sensitivity matrix obtained for the base case in both two and three dimensions. The price has been represented by colors while the variation in the installed capacity of renewable technologies can be seen in the axes. This can be seen below.



Ilustration 1: Base case Sensitivity Matrix

In the section where the analysis is developed, all the results can be seen represented and analyzed in depth. Some of the final conclusions obtained are mentioned below:

- The greater integration of renewable technologies in the Spanish energy mix leads to a significant reduction in average prices, both monthly and annual, in the day-ahead market.

- As installed renewable capacity increases, the average price decreases, but the spread between the annual maximum and minimum price increases, demonstrating that price stability is significantly affected by the integration of renewables into the system.

- In all the scenarios studied, the amount of installed wind power capacity has a greater effect on average market prices, both in terms of lowering them as more capacity is installed and in terms of making them more expensive when it is assumed that by 2025 there will be less installed capacity of this technology than expected.

- The average percentage of market price that the solar PV producer would receive per MWh will be affected to a greater extent by the integration of renewable energies into the electricity system than wind energy.

- The capture ratio of solar technology is much lower than wind in all scenarios, so the average annual wind revenue per MWh generated, in all scenarios, will be higher than that of solar.

- The minimum price achieved throughout the year shows a minimal dependence on the gas price when a substantial amount of renewable capacity is installed.

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1. Introduction

The Spanish electricity sector, and specifically the electricity market, is tremendously complex but fundamental for the correct development of our society, since this is where the energy that reaches our homes and industries is purchased and where the electricity generated in our power plants is sold.

We are currently experiencing a tremendous transformation of the sector, where renewable generation technologies are becoming more and more important, with it becoming increasingly interesting to study their impact on the day-ahead market price. The lower cost of this type of technologies and the governments' efforts to achieve a total decarbonization of the energy sector are causing a very notable increase in the installed power of these technologies and, consequently, in their presence in the generation curve of our country. This was expected to result in decreased energy prices. However, due to the rapid increase in the cost of combined cycle power plant generation since 2021 due to rising gas prices, the opposite has occurred. The price of energy has skyrocketed in the past two years, reaching unprecedented highs. The following image shows the evolution of energy prices in the Spanish day-ahead market over the last 25 years.

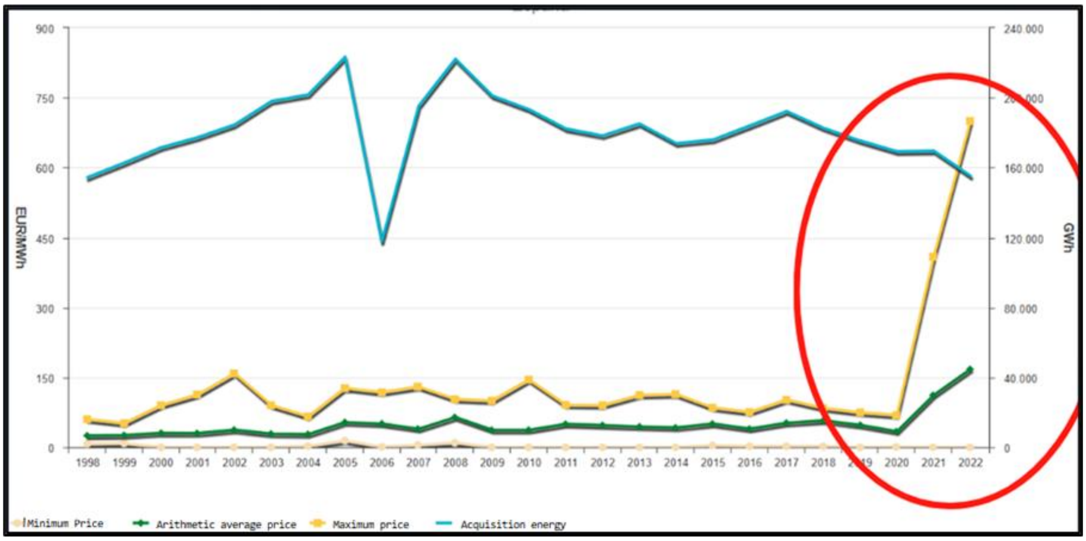


Figure 1: Historical evolution of prices in the Spanish day-ahead market. Source: OMIE

This issue is of great significance because if renewable generation were to meet the entire demand of the system and leave combined cycle plants out of the market, it would result in a major change. It's likely that the price of energy would significantly decrease, as we have observed at certain times in the past year.

This thesis aims to analyze the situation of the electricity sector and its evolution, in order to study the impact that renewable technologies will have on the Spanish day-ahead market price in 2025 under different possible scenarios. This study is important not only for investors in the sector, but also for regulators, consumers and society as a whole, as it offers a vision of the future of energy prices and the economic consequences of the transition to a more sustainable and environmentally friendly energy system.

2. Global Overview

Climate change, caused mainly by human activity and in particular by the emission of greenhouse gases, is currently one of the biggest challenges faced by humanity. This is why the IPCC (Intergovernmental Panel on Climate Change), a body dedicated to assessing the human impact on climate and proposing possible solutions, was created in 1988 to provide governments with information to develop their climate policies. In addition, every year, the countries that have ratified the United Nations conventions meet to hold the Conference of the Parties (COP), where decisions are taken on the strategy to combat climate change. These summits have agreed treaties and agreements as important as the Kyoto Protocol (1997) or the Paris Agreement (2015), where the goal of limiting global warming well below 2 degrees Celsius, preferably to 1.5 degrees Celsius, with respect to pre-industrial levels was established.

This situation has resulted in a significant transformation of the energy sector, as renewable energy sources have emerged as an alternative to fossil fuels for energy generation. Many countries have invested considerable effort into developing these technologies, which were initially inefficient but have since evolved to become a key player in the world's electricity systems. Today, with zero emissions and vastly improved efficiency, renewable energy sources are poised to revolutionize the energy sector.

2.1 Investment and costs of different generation technologies

This significant improvement in the performance of these generation sources is reflected in worldwide investments in this type of technology. Global investment in low-carbon technology projects is expected to increase by $60 billion this year, a 10% increase over 2022. This increase is driven by the development of wind and solar power, aided by a significant increase in funding for hydrogen and carbon capture, utilization and storage (CCUS) infrastructure. Below you can see a bar chart where investments in low-carbon technologies have been plotted in billions of euros, from 2019 to this very 2023.

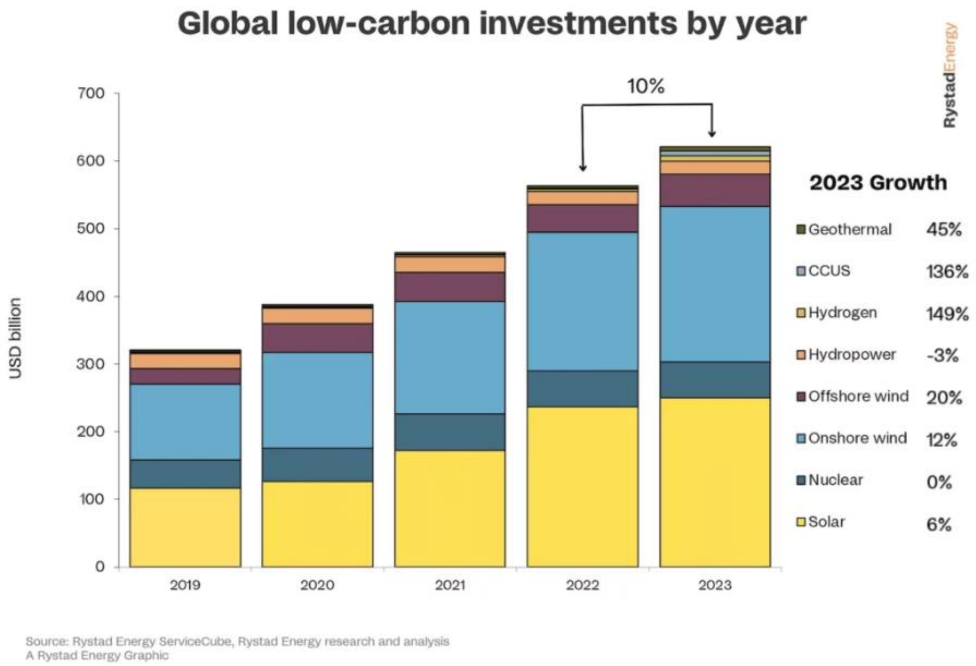


Figure 2: Global low-carbon investments by year. Source: [1]

As can be seen in the figure above, total investment will be approximately $620 billion in 2023, up from $560 billion last year. The largest increases are expected to be in hydrogen technology and CCUS, with 149% and 136% respectively. Despite this, total investment in these technologies will be $7.8 billion and $7.4 billion respectively, which is still much lower than the $250 billion investment in solar or $230 billion in onshore wind. In addition, solar investment has been clearly affected by the fall in the cost of polysilicon, the main driver of the cost of photovoltaic solar cells, which means that with only a 6% increase in expenditure compared to 2022, the increase in capacity will be approximately 25%.

This cost reduction is widespread in renewable technologies, as can be seen by reviewing their levelized cost of electricity (LCOE), which, in simplified terms, consists of calculating the total average cost of building and operating a power plant and dividing it by the total energy to be generated during its useful life, which has fallen by at least 60% compared to a decade ago for solar and wind projects. In fact, for the first time in history, the LCOE for onshore and offshore wind, tracking and fixed-axis solar are now lower than those for coal and natural gas.

Below is a graph showing the evolution of the LCOE of the different technologies mentioned over the last 10 years.

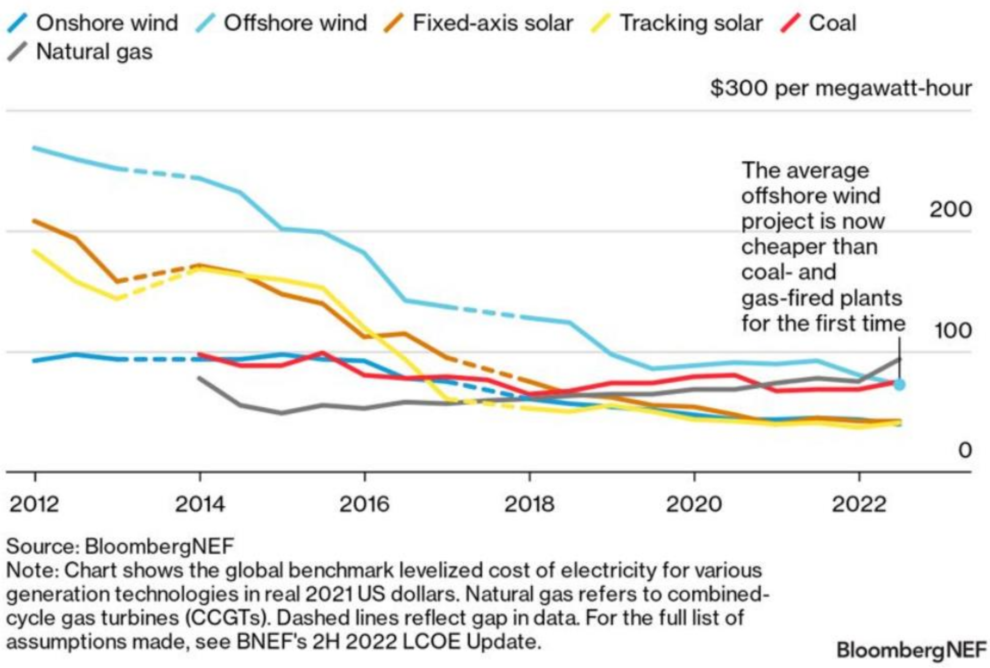


Figure 3: LCOE of different generation technologies over the last ten years. Source: [2]

It can be seen how in the last year (2022), there has been a notable increase in the cost of natural gas and coal technologies, driven by inflation and, specifically, by the high price of raw materials.

It should be said that for the integration of renewables there are two key turning points in terms of LCOE, these are:

- First, that a new wind or solar project is cheaper than building a new coal or gas plant, i.e., that renewables are the cheapest option for expanding installed capacity. This is currently the case in markets that account for 96% of global electricity generation, with onshore wind being the cheapest source in countries such as China, India and the USA.
- Secondly, that renewables are cheaper than existing fossil fuel generation assets, a threshold that has been crossed in markets comprising 60% of global electricity generation, examples being Canada, South Africa or Australia, where solar is the most attractive option.

Despite meeting these turning points, coal and gas remain the number one and two energy sources globally at this time. Furthermore, based on current trends, the anticipated growth in wind and solar projects will not be sufficient to reach net zero emissions by 2050, as despite the 16 terawatts of solar and wind power expected by 2050, it will not be enough, as an estimated 28 terawatts of these technologies are needed to reach net zero.

2.2 Net Zero Scenario

Below is a graph by BloombergNEF, where the installed capacity of solar and wind technologies are represented in an economic transition scenario explained in the note of the figure. Along with the installed capacities, the line that had to be met to achieve the net zero scenario can be seen.

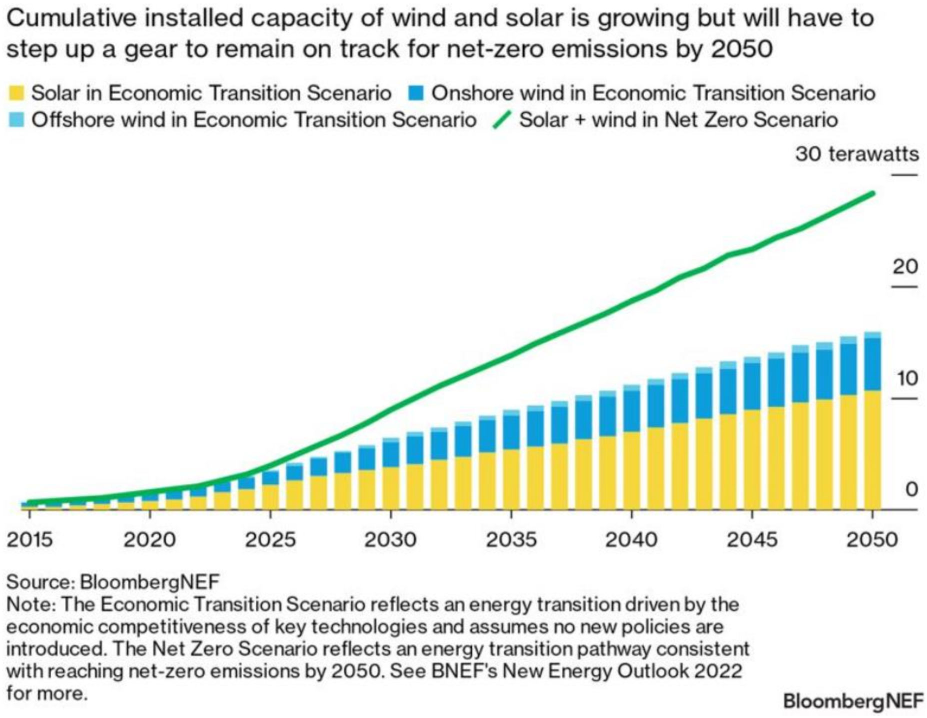


Figure 4: Renewable energy installed capacity needed to achieve Net Zero scenario. Source: [2]

As can be deduced from what has been said so far, getting rid of fossil fuels will not be easy. At present, taking into account the penetration of renewables and the rise of electric vehicles, coal and oil consumption could peak this decade, while gas consumption will peak in the early 2030s. This trajectory would cause global emissions to fall by around 30% between now and 2050, meaning that some 24 billion tons of carbon dioxide would still be emitted into the atmosphere, which would put the world on track for warming above pre-industrial levels of 2.6 degrees Celsius, in breach of the Paris agreement, which aims to limit the temperature rise to "well below" two degrees Celsius.

As the graph below shows, to reach the net zero target, fossil fuel consumption has to plummet. To achieve this, we will need to see a massive deployment of decarbonization technologies in the energy, transportation, industry and building sectors. While it is true that clean electricity sources and electric vehicles are already well advanced, the deployment of other solutions such as hydrogen electrolyzers, heat pumps and carbon capture and storage are still in their early stages.

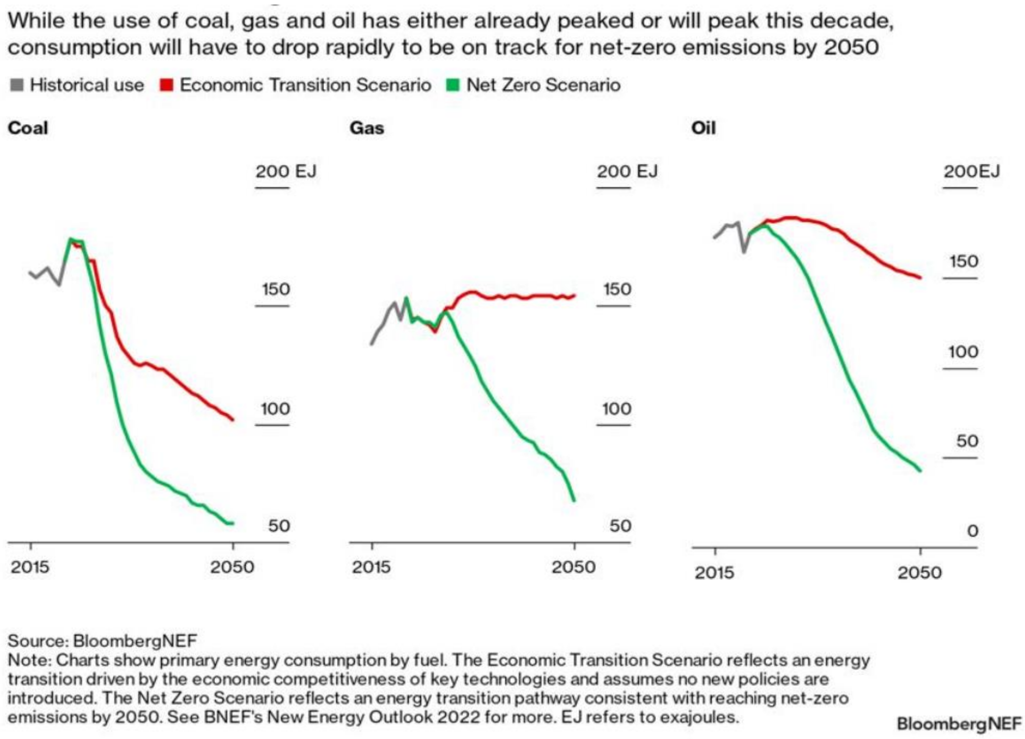


Figure 5: Fuel consumption pathway to achieve net zero scenario. Source: [2]

2.3 Carbon Markets

One of the measures adopted that could be key to moving away from fossil fuels is the introduction of carbon markets. The functioning of these markets is based on the implementation of a cap on greenhouse gas emissions that is progressively reduced. This cap is divided into emission allowances (each allowance is equivalent to the emission of one ton of carbon dioxide into the atmosphere) and, for example, in Europe, each country is allocated a limited amount of these permits. Once this is done, each country distributes these permits among companies through direct free allocation or through public auctions. After this, if a company needs to emit more emissions, it must go to the market to buy emission allowances that another company sells because it does not need them.

In Europe, this mechanism was introduced in 2005 as EU Emission Trading System (EU ETS), although it was not until 2021 that the prices of these emission allowances reached a sufficiently high value to fulfill its objective of creating an incentive for companies to reduce their emissions. Below is a graph showing the historical evolution of allowances, showing the sudden increase in the price of these from 2020 onwards. The price is measured in EUR/tCO_2.

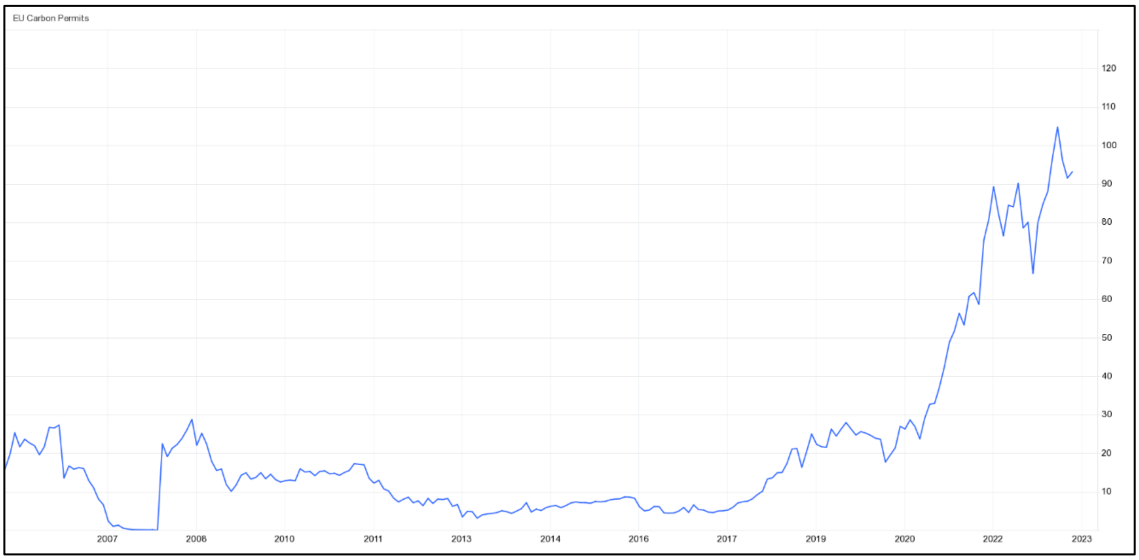


Figure 6: Historical evolution of emission allowance prices in Europe (EUR/tCO_2). Source: [3]

Globally, this type of market is relatively widespread, although in many countries the price is so low that it has no real climate impact. This is especially noticeable in sectors outside power generation, where low-carbon solutions remain too costly a proposition. Below is a graph showing the price evolution in 2022 of different carbon markets in the world, highlighting China, which being the largest market in the world, the price of emission allowances is below 10 dollars, being well below the 50 dollars that the World Bank estimates necessary to meet the temperature targets of the Paris Agreement.

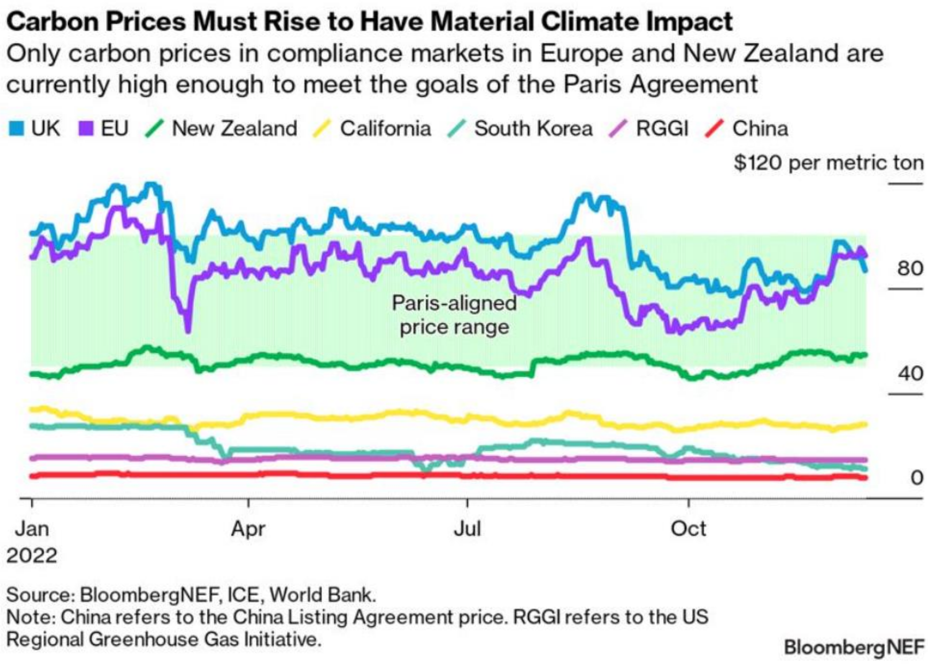


Figure 7: Global emissions allowance price evolution in 2022. Source: [2]

2.4 Storage

One technology that could revolutionize the electrical system is batteries. This technology would make it possible to store electrical energy so that it can be delivered when this energy is most valuable, changing the axiom that says that electrical energy must be consumed at the same time it is generated. The problem with this technology is its very high price, especially if we talk about conventional lithium batteries that are present in almost all electronic devices that surround us.

Moreover, in 2022, because of higher commodity and component costs, particularly for lithium, nickel and cobalt, it was the first time since 2010 that the volume-weighted average price increased over the previous year, rising by 7% over 2021, reaching $151 per kilowatt-hour, according to an annual survey conducted by BNEF. This price is key to accelerating the integration of intermittent renewable energy sources along with storage in addition to electric vehicles, with $100 per kilowatt-hour being the point at which these types of vehicles reach price parity with gasoline and diesel vehicles. The graph below shows the evolution of battery prices.

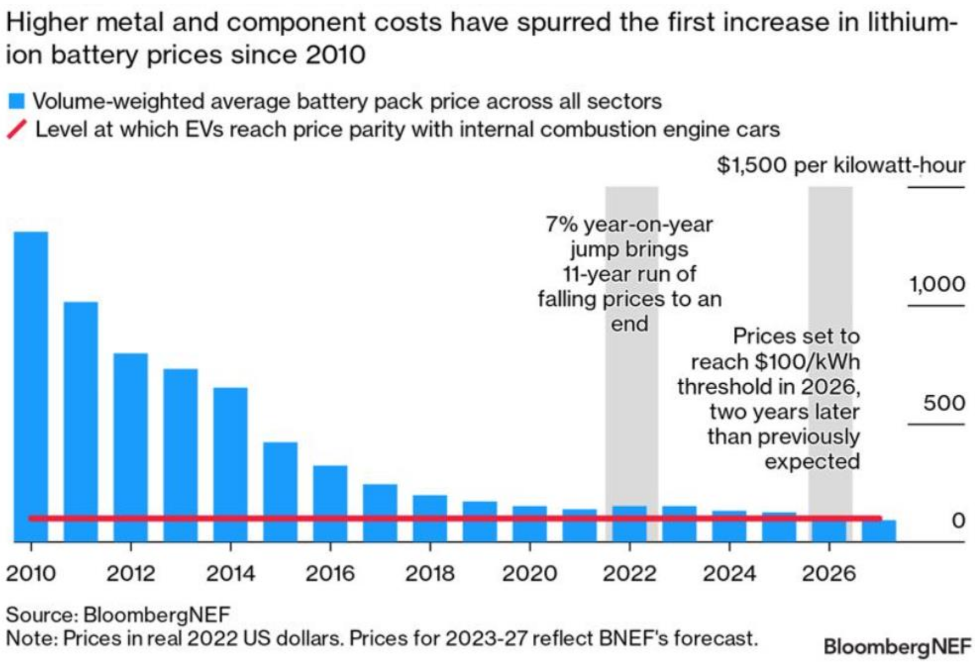


Figure 8: Historical evolution of battery prices. Source: [2]

Despite this price increase in recent years, BNEF believes that this is temporary and that the price of batteries, thanks to innovation and improvements in manufacturing, will be reduced by more than a third by 2027, reaching $94 per kilowatt hour.

2.5 Wholesale market prices

Despite the great push that renewable energies have been getting in recent years, today we continue to rely heavily on fossil fuels to supply the world's energy demand. This means that many countries are highly dependent on resources they do not have and have to import them, resulting in a dependence that can cause electricity prices to skyrocket. This is what has happened in recent years, specifically in 2022, a year in which many countries have reached record high prices, as can be seen in the following graph.

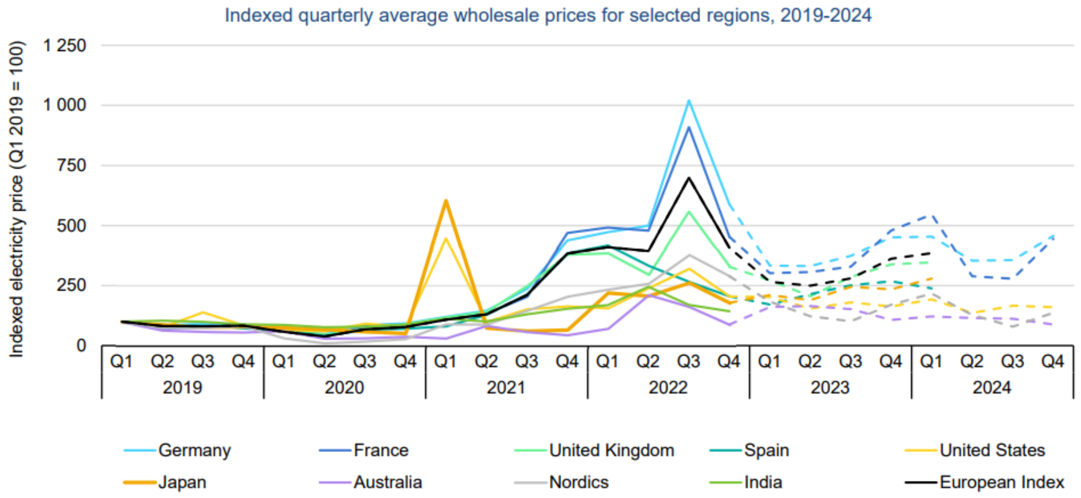


Figure 9: Indexed quarterly average wholesale prices for selected regions, 2019-2024. Source: [4]

It can be clearly seen how the price has risen significantly in recent years, with Europe being the most affected region of all, reaching, in the case of Germany, prices of over 1000 €/MWh. This uncontrolled market price has caused great commotion, even causing a possible reform of the current functioning of the market with the aim of increasing stability and, consequently, reducing volatility.

The situation on the European continent will be explained in more detail in the next section.

3. Europe Overview

Europe, and in particular the EU, recognizes that climate change is one of the greatest threats to the environment, the economy and human health. For this reason, the policies being proposed in recent years are aligned with the proposed international objectives focused on achieving a low-carbon economy and society by reducing greenhouse gas emissions through a process called decarbonization. This transition includes the implementation of various measures and strategies to reduce fossil fuel consumption and promote the use of clean energy sources.

3.1 European generation mix

Currently, the European strategy is driven by the European Green Pact, presented in December 2019, which sets out a detailed vision of how to make Europe the first climate-neutral continent by 2050, safeguarding biodiversity, establishing circular economy practices and eliminating pollution, while boosting the competitiveness of European industry and ensuring a just transition for the regions and workers concerned. In recent years, the implementation of this strategy has resulted in a steady increase in renewable energy generation capacity, with solar and wind being the most prominent technologies. In contrast, the generation capacity of traditional technologies, particularly coal-fired power plants, has declined. The evolution of the installed capacity of these technologies in recent years is shown below.

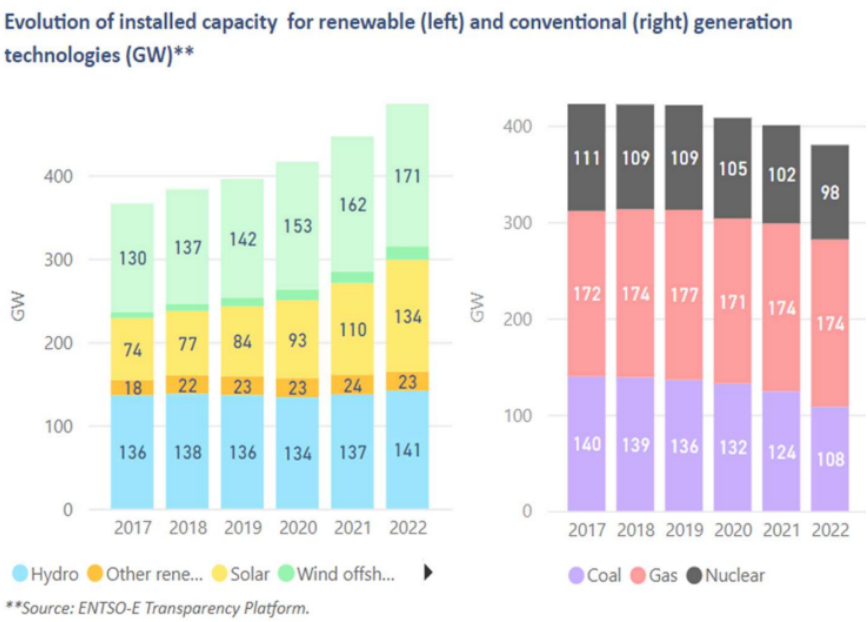


Figure 10: Evolution of installed capacity for renewable and conventional generation. Source: [5]

It can be seen that renewable technologies are indeed on the rise, with solar photovoltaic and wind power standing out above the rest. On the other hand, conventional generation technologies are decreasing, but not at the desired rate. In fact, as can be seen, the installed capacity of combined cycle (gas) power plants has not decreased since 2017, letting us see the importance that this technology currently has in European electricity systems. In addition, the greatest reduction in installed power has occurred in nuclear power plants, which not only lower the price of energy, generally, but also do not emit any greenhouse gases into the atmosphere and can greatly help to reduce greenhouse gas emissions. This shows that the criteria used to make decisions on this aspect do not seem to be the most appropriate, at least in order to achieve the goal of carbon neutrality.

3.2 Wholesale Market

This past year, 2022, has been an extremely challenging year for the energy sector in Europe. Various factors, especially the Russian invasion of Ukraine, caused the prices of one of the materials most consumed by this sector, gas, to rise even more than they had done to date, forcing Europe to take action. This increase in gas prices can be seen in the graph below, which shows the evolution of gas prices since 2021 on the TTF market, the benchmark gas market in Europe.

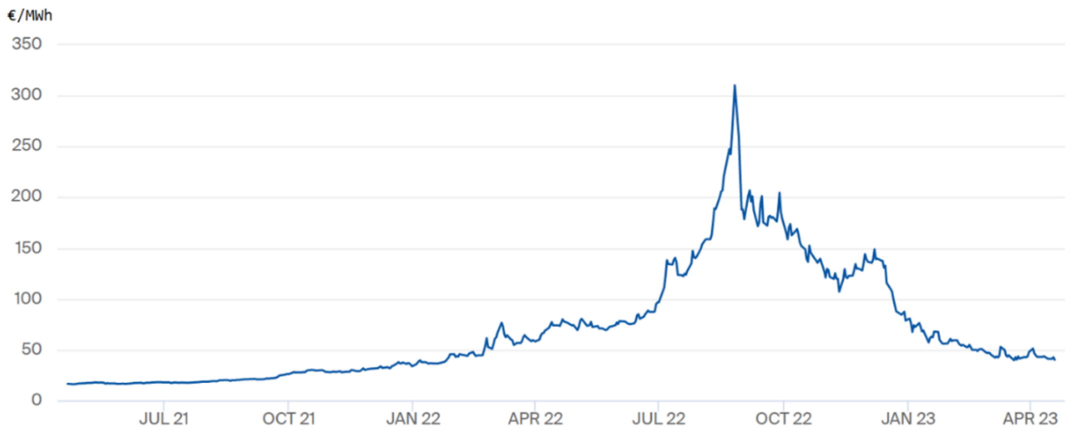


Figure 11: Evolution of gas prices from 2021 on the TTF market. Source: [6]

It can be clearly seen how the price that gas reached in 2022 was unprecedented, reaching a price of more than 300 EUR/MWh when it was not previously expected to rise above, approximately, 50. This sudden and abrupt price rise caused the wholesale electricity market prices to skyrocket because, as we have seen above, combined cycle power plants have a large presence and importance in European electricity systems and, obviously, their production costs and therefore their market offers were greatly affected by this. Below is a graph showing the evolution of the average price in the day-ahead market in different European countries in recent years.

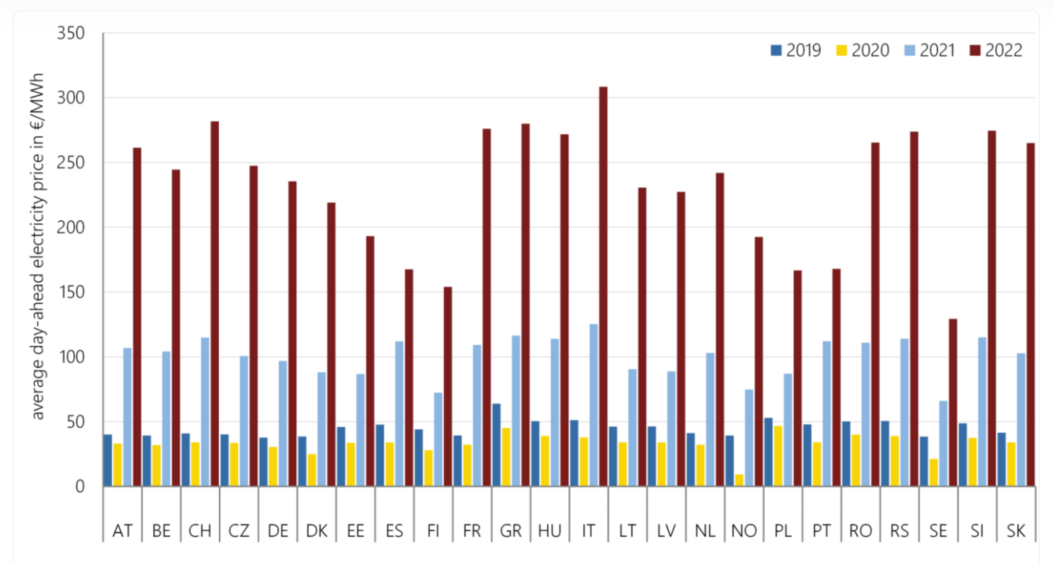


Figure 12: Evolution of the average prices in the day ahead market in different European countries. Source: [7]

To try to reduce the consequences of this, Europe's reaction was to try to accelerate its transition to clean energy by reducing gas demand and phasing out coal. This has resulted in a significant increase in clean energy production. In fact, in 2022, wind and solar energy accounted for a record fifth of EU electricity generation (22%), surpassing fossil gas (20%) and coal power (16%) for the first time.

Unfortunately, the progress towards renewable energy was hindered by two crises in Europe's electricity system. Firstly, a drought across Europe caused the lowest level of hydro generation since at least 2000. Secondly, unexpected nuclear outages occurred in France just as German nuclear units were closing down. These events created an electricity generation gap of 185 TWh, which was equivalent to 7% of Europe's total electricity demand in 2022.

Five-sixths of the electricity generation gap was filled by an increase in wind and solar energy production and a reduction in electricity demand. However, the remaining sixth was met by increased fossil fuel generation, mainly coal. As coal was less expensive than gas, it accounted for the majority of the increase, rising 7% (28 TWh) in 2022 compared to 2021. As a result, EU power sector emissions increased by 3.9% (26 $MtCO_2$) in 2022 compared to 2021. The evolution of the share of electricity generation by technologies in Europe is shown below.

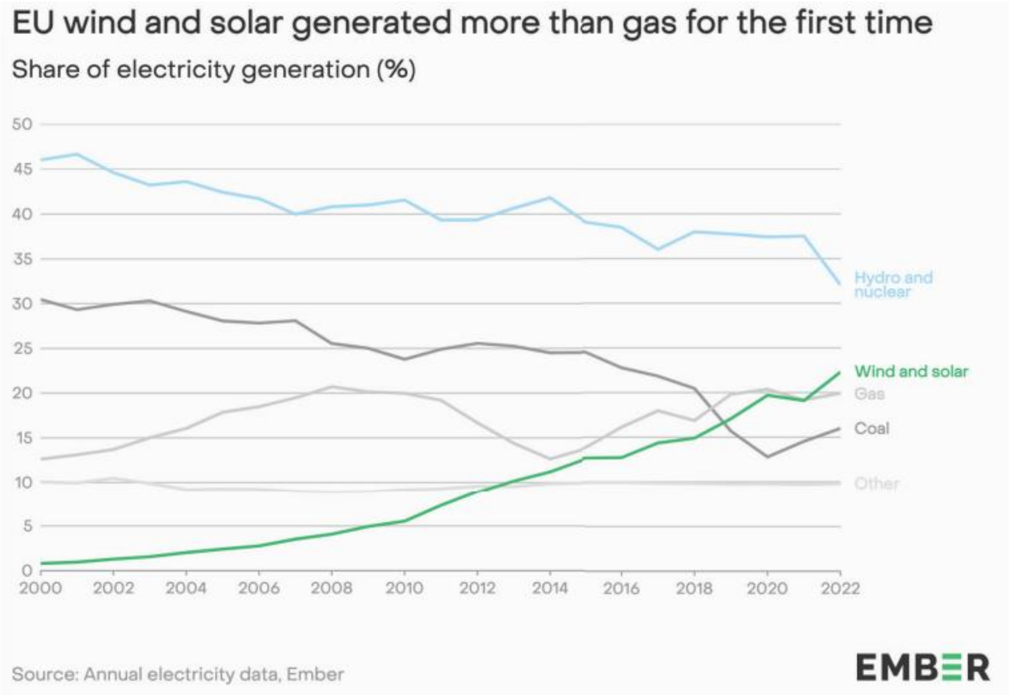


Figure 13: Evolution of electricity generation share by technology in Europe. Source: [8]

The far-reaching consequences of the energy crisis have resulted in a notable change in policy priorities within the European Union. In reaction to the crisis, the European Commission released its REPowerEU plan on 18 May 2022, aimed at expediting the transition to clean energy and reducing the EU's reliance on Russian fossil fuels. Subsequently, in December, a Council regulation was adopted to establish a provisional framework that would facilitate the expansion of renewable energy sources. In addition, the Commission initiated a consultation on electricity market design in early 2023, prompted by the record-high prices of electricity.

National short-term measures were implemented to alleviate the strained market situation and provide relief to consumers. These measures included the introduction of price caps, energy tax reductions, and the regulation of retail tariffs, among various other initiatives. Several countries have taken steps to decrease gas demand in the power sector and bolster supply security during the 2022/23 winter, including the reactivation of reserve generation capacities, mainly composed of coal-fired plants. For example, in Germany, the three remaining nuclear reactors have been shut down, and coal-fired power plants have had to supply most of this energy. All these events have led to a significant change in the European electricity system and, specifically, in the volume of generation produced by each technology with respect to 2021. These changes are shown below.

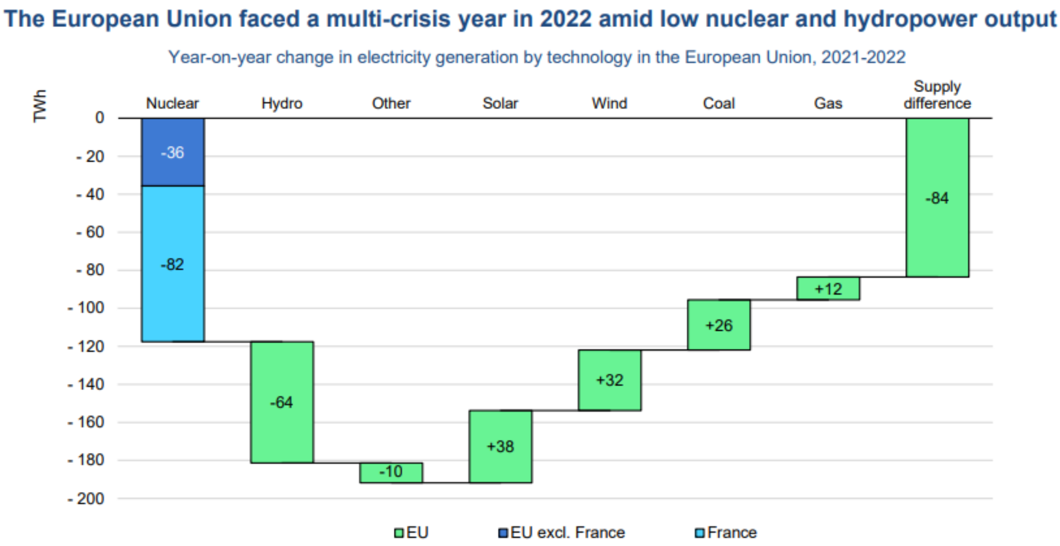


Figure 14: Year-on-year change in electricity generation by technology in the European Union, 2021-2022. Source:[9]

Once the global and European situation has been analyzed, a series of fundamental economic concepts will be explained in the following section in order to understand in detail the functioning of the day-ahead market and thus carry out the final objective of this thesis, to evaluate how the integration of renewable energies affects the market price.

4. Fundamental economic concepts

To comprehend the mechanics of the electricity market, it is crucial to have a grasp on various fundamental concepts. One of the essential concepts is the understanding of what a market means. In economics, a market encompasses a broad range of ideas, and it is defined as a medium that enables the interaction between buyers and sellers for the purpose of facilitating a transaction. To understand how a transaction works, it must be clear that the value of a good is not the same as the price of that same good. Value is subjective and depends on the needs of each agent; if value were not subjective, exchanges would not take place. For exchanges to take place, both agents must feel that they benefit, valuing what is received more than what is given. In summary, it can be said that price is what you pay and value is what you get.

Once this concept is clear, it is necessary to know that there are different types of markets and that they can be distinguished from one another based on several criteria, which help to define the nature and characteristics of the market. These criteria include:

- Organization: Markets can be organized or unorganized, depending on whether buyers and sellers meet at a specific time and place, either physically or online, and whether an auctioneer is involved in the transaction. Organized markets tend to be more formalized and structured, while unorganized markets may be more flexible and informal.

- Competition: The degree of competition in a market depends on the number of buyers and sellers, as well as the ease with which new buyers and sellers can enter the market. More competition generally leads to lower prices and greater efficiency in the market. Markets can be classified as more or less competitive based on the number and size of buyers and sellers.

Demand → / Supply ↓	**Many buyers**	**Few buyers**	**Sole buyer**
Sole seller	**Monopoly**	Partial monopoly	Bilateral monopoly
Few sellers	**Oligopoly**	Bilateral oligopoly	Partial monopsony
Many sellers	**Perfect competition**	Oligopsony	Monopsony

Figure 15: Types of markets based on competitiveness. Source: ICAI

- Information: Markets can also differ in terms of the availability and quality of information to buyers and sellers. In a perfect information market, all buyers and sellers have access to complete and accurate information about the product or service being traded. In contrast, an imperfect information market is one where some buyers or sellers have an informational advantage over others, leading to potential market inefficiencies.

- Intervention: Markets may also be differentiated based on the degree of government or other regulatory intervention. In some cases, governments may place restrictions on the buying and selling of certain goods or services or impose price controls or other regulations to protect consumers or promote certain societal goals. If there is no intervention whatsoever, it is called a free market.

4.1 Law of demand and supply

After gaining an understanding of the concept of the market, the next step is to delve into the process of price determination for a particular product. In a free market, the price of a product is determined by the interplay of the amount of supply and the level of demand for the product, which is commonly referred to as the law of demand and supply. This fundamental economic principle states that as the level of demand for a product increases, while the level of supply remains constant, the price of the product rises. Conversely, when the supply of a product increases while demand remains constant, the price of the product decreases. These concepts are explained in detail below:

- Supply: Quantity of a product, such as electricity, that is available for purchase at a particular price point. In a market, an increase in the price of a product acts as a signal for suppliers to increase the quantity of the product they produce. This response to the price signal is represented by the upward sloping supply curve, which shows that as the price of the product increases, so does the quantity of the product supplied. A basic illustration of a supply curve is depicted below:

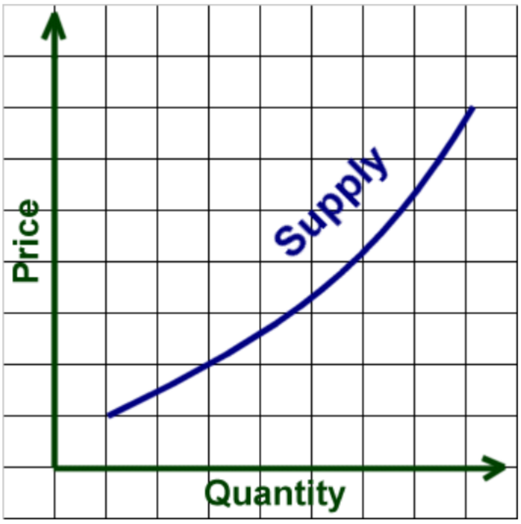


Figure 16: Supply curve. Source: [10]

- Demand: Quantity of a product, such as electricity, that buyers are willing to purchase at a given price point. In a market, an increase in the price of a product leads to a decrease in the quantity demanded of that product, as per the law of demand and supply. This inverse relationship between price and quantity demanded is represented by the downward sloping demand curve, which shows that as the price of the product increases, the quantity demanded of that product decreases. A basic illustration of a demand curve is depicted below:

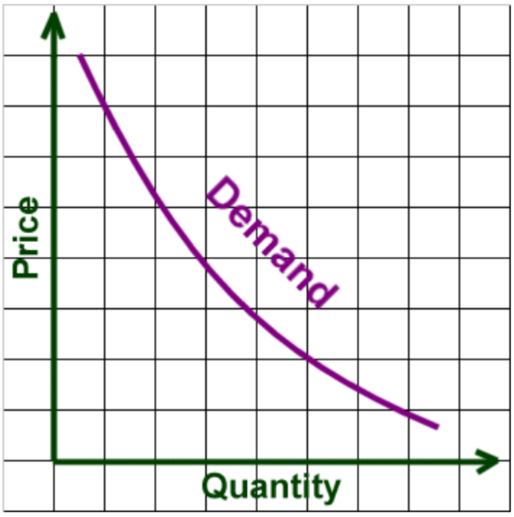


Figure 17: Demand Curve. Source: [10]

When we overlay these two curves, there is a point where they intersect, which is referred to as the market equilibrium point. At the market equilibrium point, the quantity of the product demanded by consumers is exactly equal to the quantity supplied by producers. This means that the market is in a state of balance, where the price of the product is stable and there is no excess supply or demand.

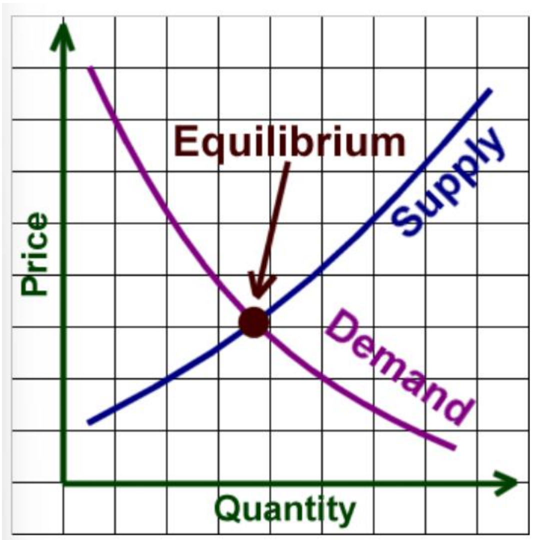


Figure 18: Equilibrium point. Source: [10]

In a free and perfectly competitive market, the price of a good will tend to reach the equilibrium point over time. This is an economic axiom based on price signals sent by the market to both consumers and producers. For example, if the equilibrium price for a good in a free market is 4 euros but transactions are currently occurring at 3 euros, consumers will demand more units than producers are willing to sell, creating excess demand. The consequence of this is that the market is sending a price signal to producers to raise the price until this excess demand ceases to exist. Conversely, if the price is above the equilibrium price, excess supply will be created, leading to a drop in prices. These phenomena are depicted below.

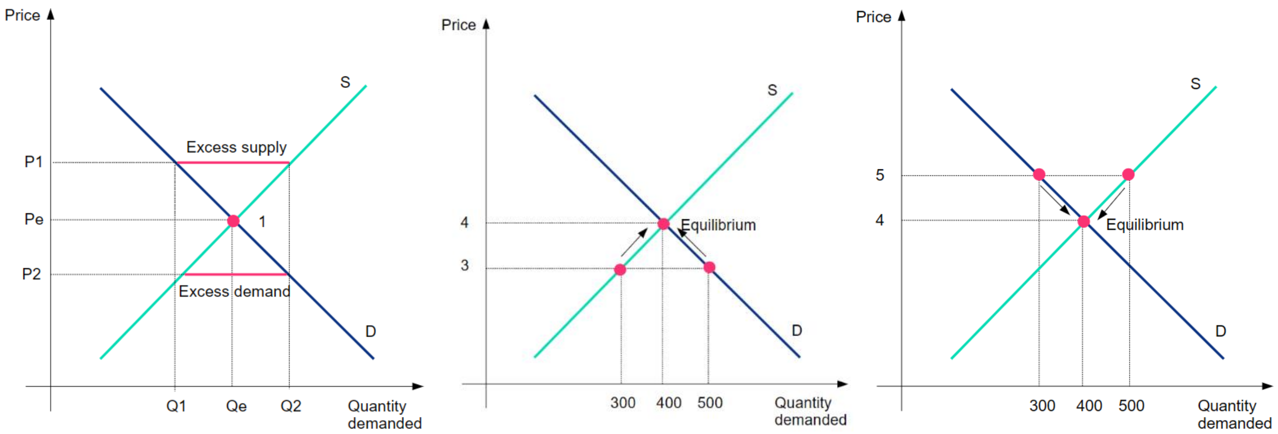


Figure 19: Excess supply and demand. Source: [11]

It is important to emphasize that this scenario would be fulfilled in a free market of perfect competition with a single product. In other market structures, the demand and supply curves may fluctuate due to external factors, rendering the equilibrium point unstable. Therefore, it is essential to take into account the specific conditions of the market in question when analyzing the interplay between supply and demand. Various factors can influence the demand curve, thereby affecting the equilibrium price and quantity. For instance, changes in consumer preferences, income, population size, and availability of substitute goods or services can all shift the demand curve. Other variables such as advertising, marketing, and promotional campaigns can also impact demand. Thus, it is vital to consider these factors when examining the dynamics of a particular market.

In addition to the factors that can move the demand curve, there are also factors that can influence the supply curve. For example, changes in production costs, technology, or government regulations can all shift the supply curve. A decrease in production costs, for instance, could cause the supply curve to shift to the right, leading to an increase in the quantity supplied at any given price. On the other hand, an increase in production costs or regulatory burdens could shift the supply curve to the left, resulting in a decrease in the quantity supplied at any given price. It is important to note that these factors can also interact with each other and affect both the demand and supply curves simultaneously. Ultimately, the interplay of these factors will determine the location of the equilibrium point and the resulting market price and quantity.

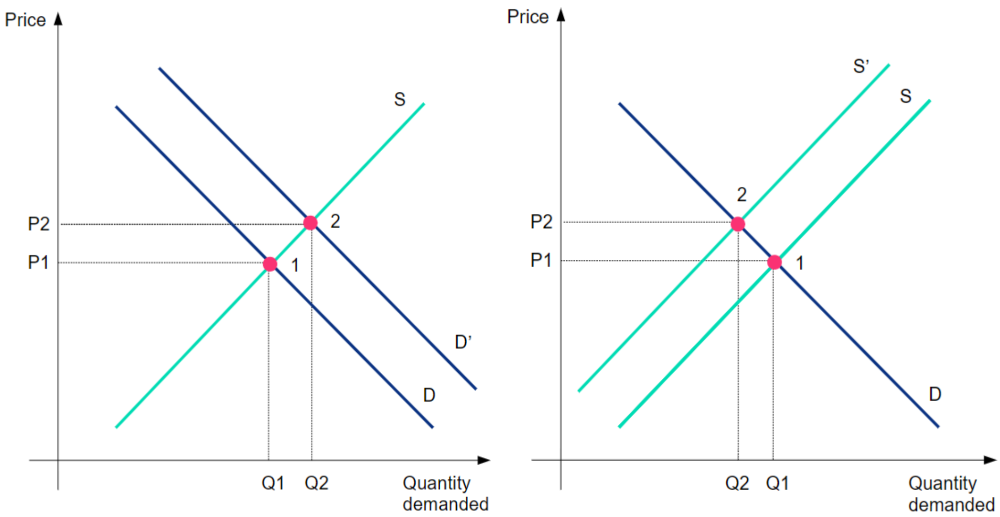


Figure 20: Demand and Supply curves shifts. Source: [11]

4.2 Social welfare

As previously explained, the demand and supply curves are used to represent the price at which consumers and producers are willing to buy or sell a quantity of a product. Knowing this, it can be deduced that the difference between the market price, which is the equilibrium point at which the quantity demanded is equal to the quantity supplied, and what consumers and producers are willing to pay or charge is called surplus. These surpluses are known as consumer and producer surplus and are represented visually in the following chart.

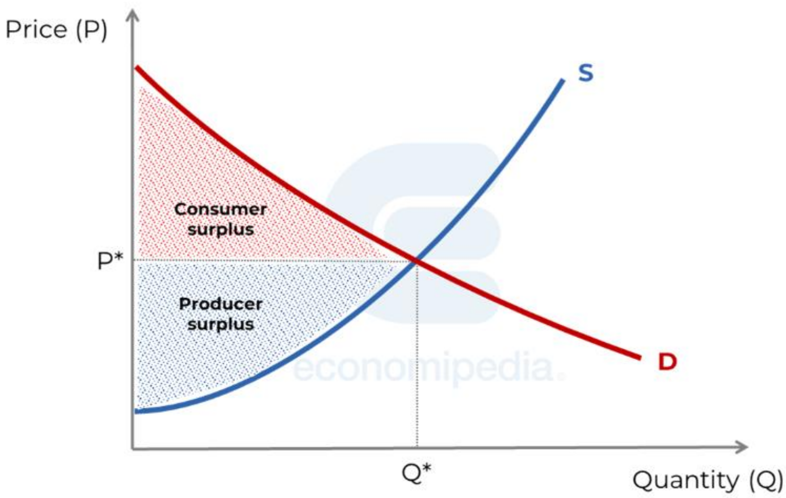


Figure 21: Consumer and Produces Surplus. Source: [12]

This is why the equilibrium point is so important, since it establishes the optimal price at which "everybody wins", both consumers and producers are satisfied, as consumers pay less for the product than what they are willing to pay, and producers receive more than what they would accept. Moreover, it could be said that the sum of these two surpluses forms the social welfare, hence, an ideal market would aim to maximize the red and blue shaded areas in the figure to achieve the greatest social welfare. In fact, the algorithms used for the bid matching process in the market, a process that will be explained in detail later, are usually aimed at increasing social welfare as much as possible.

However, this system by which demand and supply are self-regulated (invisible hand) according to the price signals offered by the market, is not always efficient for different reasons, known as market failures. Some of these are:

- Nature of the goods
  - Externality: Impact of one person´s action on the well-being of a bystander with no cost/reward associated. For example: Pollution.
  - Non-excludability: Sellers are unable to exclude buyers from using the service.

- Nature of the exchange
  - Transaction costs: Cost of making the economic trade.
  - Information asymmetry: One party has more or better information than other.

- Nature of the market
  - Imperfect competition: Refers to the ability of a single person (or small group of people) to influence market prices. For example: Monopoly.

In addition to this, the invisible hand is less able to ensure that economic prosperity is distributed fairly. For these reasons, a government can intervene in an economy, seeking to promote efficiency and equity. But not all that glitters is gold, since this intervention, if not done cautiously, can be a remedy worse than the disease. For example, let us imagine the situation in which the government, for some reason, considers that the producers of a certain good are earning more money than they should and, as a consequence, imposes an extraordinary tax on them. The producers, having more costs than before, will have to supply that good more expensively than before the tax, shifting the equilibrium point as follows:

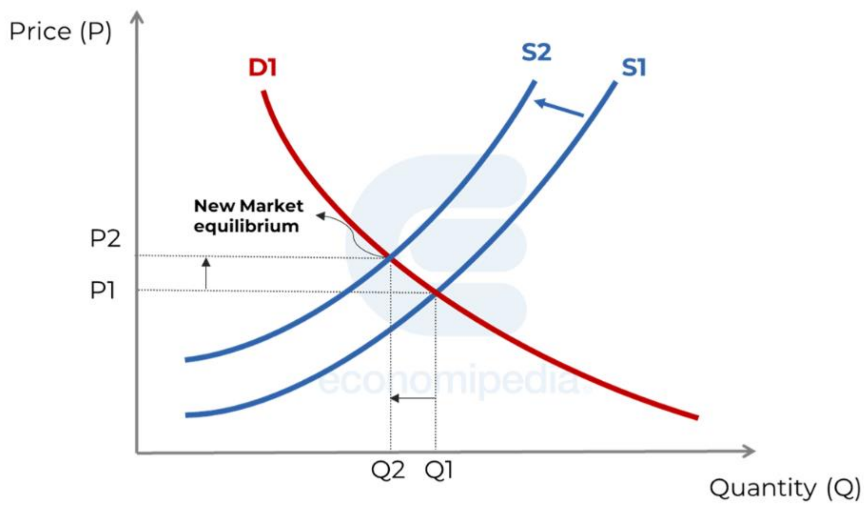


Figure 22: Supply curve shift because taxation. Source: [12]

4.3 Ramsey taxation

The consequences of this are explained by what is known as the Ramsey taxation. The Ramsey taxation refers to the challenge of setting optimal taxes on different goods in an economy. The goal is to generate sufficient revenue for the government while minimizing the deadweight loss, or the loss of economic efficiency that results from taxes. This loss occurs when a tax is not set at the level that maximizes the total welfare of the society. Rather than being based on economic efficiency or fairness, a tax may be implemented by the government to meet revenue targets or to redistribute wealth. This can have a negative impact on the market equilibrium, leading to a decrease in the overall welfare of society, as evidenced by a decrease in both consumer and producer surpluses.

The deadweight loss in a market is determined by the elasticity of demand and supply. When the demand for a product is inelastic, it means that consumers are not very responsive to changes in price, and so the market can tolerate a larger tax or other price distortion without causing a significant reduction in the quantity exchanged. In this case, the deadweight loss will be smaller. On the other hand, when the demand is elastic, consumers are highly responsive to changes in price, and so even a small tax or price distortion can cause a significant reduction in the quantity exchanged, resulting in a larger deadweight loss.

Once the fundamental economic concepts have been understood, it is time to learn about the specific and detailed functioning of the day-ahead energy market, thus being able to fully understand the current situation, and to analyze in detail the impact that renewable energies will have on this market in 2025.

5. Day-Ahead Market

Once the basic knowledge of how markets work has been acquired, this section will delve into the ins and outs of the Spanish electricity market, focusing on the day-ahead market, where most of the energy is traded. Apart from the day-ahead market, there are also intraday markets where agents can make transactions during the day in order to adjust their generation and consumption. However, for the purposes of this thesis, it is not necessary to explore the workings of these markets, and therefore their explanation will be omitted.

First, to understand how this complex market works, it is necessary to understand the peculiarities of the product being traded.

5.1 Product features

As explained above, the market is a place, physical or virtual, where products are exchanged. In this case, the product to be exchanged is electricity, which is a unique product due to its physical characteristics. These characteristics are explained below:

- It is not economically viable to store large amounts of electricity, which means that, at any time electricity is to be consumed at any point in an electricity system, that electricity must be generated at that or another point. The consequence of this is that the value of electricity, and consequently the price, varies as a function of time.

- Electricity flows through the grid cannot be controlled in a simple and efficient way. This means that electricity has a different value with respect to space because there will be places where it is more expensive to generate a certain amount of electricity and deliver it to its destination due to technical reasons of the grid through which the electricity is transmitted. Despite this, it should be noted that the final quality of the product does not depend at all on its origin. In other words, a unit of electricity produced by a coal-fired power plant, for practical purposes for the consumer, is the same as a unit produced by solar panels.

- Demand and generation must always be equal. This is essential when operating a power system, since the demand and availability of certain energy sources such as renewables can vary sharply in a relatively short time, while other sources, such as nuclear, need a long time to start or stop generation. The consequence of this is that the ability to vary a plant's generation or a given agent's demand quickly is of great value.

5.2 Agents involved

Firstly, to understand which agents are part of the electricity market and why, it is necessary to differentiate between the two environments in which the different activities included in an electricity system are carried out. The reason why there are two different environments is based on the benefits and disadvantages that may arise from the presence of rivals in a given activity.

1. **Highly regulated environment**: In this environment the presence of rivals is not beneficial to society as a whole and therefore the activity in question is said to be under a natural monopoly regime. The clearest ideal example for this environment is the construction and operation of the transmission grid. Being such a costly and bulky asset to implement, as well as being tremendously complex to operate, it does not make sense for different rivals to build and operate their different high-voltage grids.

2. **Competitive environment**: In this case the presence of rivals means a benefit for society as a whole. The clearest example for this environment is the electricity generation activity, since, in this case, the presence of these rivals does not imply inefficiencies for the system as a whole, since the different rivals will try to obtain the most efficient technologies in order to be able to sell their energy at a lower price and gain a foothold in the market. This contributes both to lower prices and to the use of resources.

The following is a more detailed explanation of the agents involved in the electricity system and, consequently, in the electricity market.

- **Generation**: As mentioned above, the agents involved in electricity generation operate in a competitive environment. As expected, the way in which this energy is generated has a significant influence on the price, since some technologies are more expensive than others when it comes to generating electricity. In Spain, the presence of renewable energy in the system stands out, being approximately 60% of the installed power in the system, so this thesis, which aims to analyze the impact of this technology on the market price, has special relevance in this country.

- **Transmission**: As mentioned above, this activity is a natural monopoly, with a single agent in charge of carrying out the transmission activity, which refers to the transmission of electricity through the high-voltage grid of an electricity system. This agent is known as the transmission system operator (TSO), and in Spain, the company designated to perform this function is Red Eléctrica. Red Eléctrica, as system operator in Spain, owns all the infrastructure that makes up the high voltage grid. It is also responsible for operating this infrastructure in accordance with the quality standards established by the national regulator, in this case, the National Markets and Competition Commission (CNMC).

- **Distribution:** This activity encompasses everything necessary to connect the transmission networks to the places of consumption, whether at medium or low voltage. It is a highly regulated activity, and the remuneration of the companies that carry out this activity is set by the national regulator. Due to the large extension of the transmission network, there are different companies engaged in this activity, although there are only five that control 90% of the market.

- **Commercialization**: These are the agents in charge of acting as intermediaries between end consumers and generators. They buy energy in the wholesale electricity market and then sell it in the retail market to consumers. The latter will decide who to buy it from according to their needs and the offer of each supplier, being able to choose the most suitable one in an ideal case. These tariffs proposed by the suppliers must be approved by the national regulator.

- **Market Operator**: This agent has a special and very specific function within the electricity sector, which is to manage the electricity market. The agent in charge of this function is called NEMO (Nominated Electricity Market Operator), according to European terminology. In the Iberian Peninsula, the company in charge of this function is OMIE.

5.3 Marginalist electricity market

Once the different activities that take place in the electrical system are known, it is time to understand how the energy is exchanged and why it is done in this way.

First of all, it is essential to know the market model used since 1997 for the Spanish day-ahead electricity market, called the 'marginalist market'. In this type of market, the price of electricity is set by the supply curve, made up of the bids of all the power plants that can sell their electricity, and the demand curve, made up of the bids of the buyers. Once the two curves are available, they overlap, cutting at a single point. As an example, it has been decided to represent the supply and demand curves of February 24, 2023, for hour 8 of MIBEL, which refers to the Iberian electricity market, encompassing Spain and Portugal.

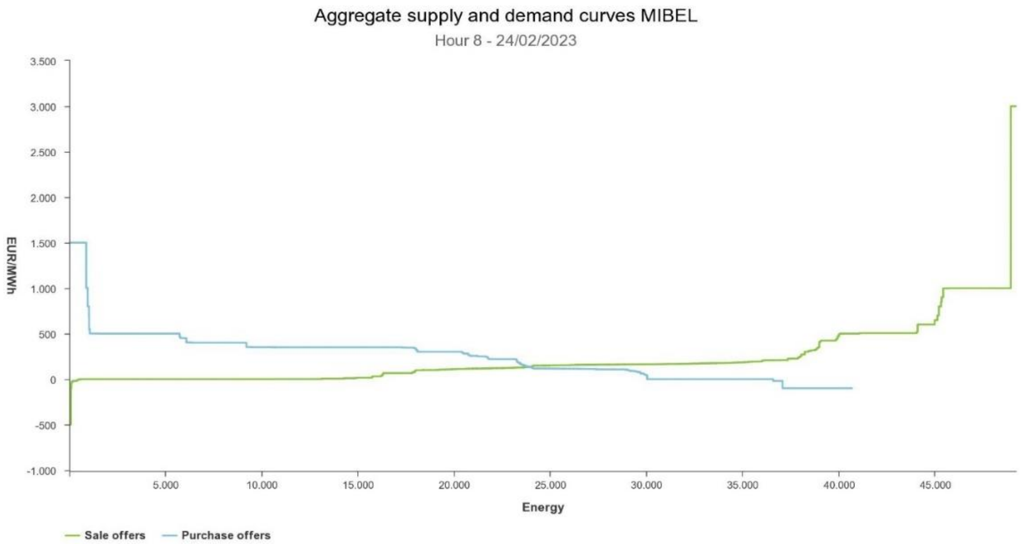


Figure 23: Aggregate supply and demand curves MIBEL, Hour 8 – 24/02/23. Source: OMIE

The intersection of the curves with the energy sale and purchase offers for that hour on that day can be clearly seen. This point, previously called the equilibrium or break-even point, would determine the remuneration for each and every plant that has entered the matching, i.e., for all plants located to the left of this point of intersection of the curves.

This means that, regardless of the offer made by a generating plant in the market, if it has entered the matching, it will receive a monetary amount for its units of energy equal to the price resulting from the intersection of supply and demand. This is because this price is the market price necessary to supply the entire demand for electricity through the power plants available at that particular time. In this way, social welfare is maximized, achieving the objective set at the time of designing the market.

The advantages of having this type of market are mainly two:

1. All producers are encouraged to disclose their real cost structure, i.e. at what price they are actually willing to sell electricity. This is so for an obvious reason: the producer does not gain anything by bidding his energy at a higher price than he would be willing to sell it, since, in case of entering the matching, he would not earn more money than if he had bid 'honestly', since all generating plants receive the same remuneration, and furthermore, by making this overbid the only thing the producer can achieve is to remain outside the matching, and therefore, without being able neither to produce nor to sell his energy.

2. It allows us to know through the market which types of power plants are, in each place and time, relatively more profitable. It must be taken into account that, although certain plants will receive profits from selling electricity at a higher price than they would be willing to sell it, with those profits they obtain in the wholesale market they have to cover all the fixed costs of these plants. Therefore, not all the profit they make in this marginalist market is a final net profit; the amortization of these plants, i.e., the recovery of the initial investment cost of building the power plant, must be included. In any case, if through the marginalist market these plants obtain extraordinary profits, even after covering their fixed costs, what will happen is that the market will be telling investors that they have to invest more in this type of power plants, because they are plants that produce electricity more cheaply than the competition. Therefore, the market establishes a price signal for investors, encouraging investment in this type of power plants that are relatively cheaper than the others. Thus, it is only a matter of time before these types of plants, which are capable of generating cheaper electricity, cover the entire demand.

In short, this market, on the one hand, makes producers reveal their real cost structure and therefore, at any given moment, those who supply electricity are the most efficient plants when it comes to generating that electricity and, on the other hand, it provides incentives to direct investment towards those plants that are relatively more profitable than the others because they are capable of generating electricity more cheaply than the remaining technologies.

Once the marginal market is understood, the operation of the day-ahead market will be explained.

5.4 Operation of the day-ahead market

5.4.1 Market characteristics

Due to the peculiarities of electric energy, there are different markets where it can be traded, being able to differentiate between organized and non-organized markets. For the sake of the thesis, this section will explain the functioning of what is called the day-ahead market, which is part of the organized markets.

The purpose of the day-ahead market is to carry out electricity transactions for the following day through the submission of bids for the sale and purchase of electricity by market agents. These market agents are mainly traders with the objective of buying electricity to subsequently sell it to consumers, and generators with the objective of selling the energy they will generate the following day. The bids made by the different agents will be submitted to the market operator (OMIE), and will be included in a matching procedure taking effect for the daily scheduling horizon, corresponding to the day after the closing day for the reception of bids for the session.

It should be noted that all available production units, i.e., all available power generation plants, that are not part of a physical bilateral contract, i.e., that do not have a purchase and sale agreement in the over-the-counter market, are required to submit bids for the day-ahead market for the remaining energy not committed in the bilateral contract.

5.4.2 Submission of bids

Starting in 2014, at 12:00 CET every day, the day-ahead market session is held for the whole of Europe. During this session, the price of electricity for the twenty-four hours of the following day is established for the entire continent. It is important to note that this price is not uniform for all European countries, although if there were interconnections with infinite capacity between them, it would be. This means that each country may have different prices due to factors such as internal supply and demand, local power generation and associated costs.

Once this is known, it is important to know the methodology when making sales offers in the market. These can be simple or complex depending on their content. Simple bids are economic offers for the sale of energy that sellers submit for each hourly period and production unit they own, consisting of a price and an amount of energy. On the other hand, complex bids incorporate a number of technical or economic conditions that may condition the final acceptance of the bid in the market. These conditions are as follows:

1. **Indivisibility condition**: Allows a minimum operating value to be set in the first tranche of each hour. This value can only be divided by the application of distribution rules if the price is different from zero.

2. **Minimum income condition**: As its name indicates, this condition allows requiring a daily income above a certain amount. This amount is divided into a fixed amount, established in euros, and a variable remuneration, established in euros for each MWh contracted.

3. **Scheduled stop condition**: This condition allows that, if the generating unit has been withdrawn for not meeting the minimum income condition, it can make a scheduled stop in a maximum time of three hours. In other words, the generating unit will be given three hours to stop its production, thus not having to stop from its program in the last hour of the previous day to zero in the first hour of the following day. This condition has the requirement that the energy offered in those hours must be decreasing in each hour.

4. **Load gradient condition**: This condition allows the producer to establish a maximum difference between the matched energy of one hour and the next, thus avoiding abrupt changes in units that, technically, cannot vary their production so quickly.

5.4.3 Bid matching process

Having understood how bids are made in the market, it is necessary to understand the bid matching process. This matching is carried out by an algorithm called Euphemia. This algorithm seeks to optimize the economic surplus, which corresponds to the sum for all the hourly periods of the scheduling horizon of the profit of the purchase bids, plus the profit of the sale bids, plus the congestion rent, marked by the transmission lines. The benefit of the purchase offers is understood as the difference between the price of the matched purchase offer and the marginal price received, and the benefit of the sale offers is understood as the difference between the resulting marginal price and the price of the matched sale offer. The Euphemia algorithm matches stepwise aggregate curves, where the start and full acceptance prices align, and interpolated aggregate curves, where there is a minimum difference between the start and full acceptance prices. It ensures high precision in price and energy values beyond the decimal limit for bid submission. After matching, values are rounded based on market-specific accuracy (two decimals for prices and one decimal for energies in the Iberian market).

Euphemia considers complex conditions and block conditions for bids, following the rules of the day-ahead and intraday markets. Results are constrained by interchanges between production zones, limited by available capacity communicated by system operators. All individual bids in a zone are treated as a single bid. Once matching is complete, the market operator allocates matched and unmatched blocks in each zone. Matched and unmatched energy blocks are assigned for bids with complex conditions (excluding indivisibility) and bids without complex conditions or with only the indivisibility condition.

Finally, once the market matching has been performed, the results of the process are sent to the system operator, in the case of Spain, Red Eléctrica, which must evaluate the results from a technical point of view. This process carried out by Red Eléctrica is called 'management of the system's technical restrictions' and its objective is to ensure that the results obtained in the matching are technically feasible in the transmission grid. It should be noted that all consumers are entitled to receive the energy they have purchased in the market, however, producers are not entitled to produce all the energy sold, as due to technical constraints in the grid it may not be possible for a certain generation unit to produce energy at a certain time.

5.5 Types of power generation

Once the functioning of the day-ahead market is known, it is important to understand why the different generation technologies bid the energy they produce at different prices in the market and how this affects the matching of bids and, consequently, the final price of the day-ahead market.

When performing the day-ahead market bid matching process, OMIE only takes into account the economic conditions of the bids submitted by the generators. These bids, as can be seen in the figure above, are ordered from cheapest to most expensive until the curve crosses the demand curve and the break-even point is reached. Knowing this, it is of great interest to know which technologies make up the supply curve and how these technologies offer their electric power in the market.

First of all, it is important to note that power plants have two types of costs: fixed costs and variable or marginal costs. Simplistically, fixed costs are those that the producer must assume regardless of the volume of production, while variable costs depend exclusively on production. With this information in mind, it is easy to deduce that the costs of different power generation technologies will vary, as some may have high fixed costs but low marginal costs, and vice versa. In the following, the behavior of the most relevant generation technologies in the electricity market will be explained in terms of these costs.

- **Nuclear:** This technology has very high fixed costs but low variable costs. These high fixed costs are due to the fact that the construction of a nuclear power plant is a work of enormous magnitude, which requires not only a lot of money but also a lot of time. It is a technology that generates electricity constantly thanks to its fuel, uranium, which makes it possible for these plants to stop producing only for maintenance. But this also has its disadvantages, since these plants cannot be switched on or off in a short time, but need careful planning for their operation. All these factors mean that this type of technology offers its electrical energy very cheaply on the market, and its bids are even negative, since the cost for the producer to stop the plant is very high and he is willing to pay for someone to consume his energy. Moreover, at least so far, there has never been a negative price in the Spanish day-ahead market (although a zero price has occurred for many hours), so for the time being it has not been necessary for these producers to pay to generate energy. In short, nuclear energy lowers the market price and does so throughout the day, since its production is constant during all hours.

- **Renewable energies**: For this section, no distinction will be made between the different renewable technologies such as solar photovoltaic or wind power, since their behavior is very similar in the market (although not identical). This type of technology has relatively low fixed prices, since the magnitude of these plants is not as large as conventional power plants, and variable costs are practically nil, since the fuel is free and unlimited, for example sun or wind, and the maintenance costs caused by the use of these installations are not very relevant. The big problem with this type of technology is that they are intermittent generation, i.e., they cannot generate energy whenever they want, but only when the natural resource necessary to operate them is available. This is a major problem when it comes to operating these plants, since the weather forecasts needed to know whether the resource will be available at a specific time and place are not an exact science, but can be right or wrong, which can result in high costs for the producer. In the day-ahead market, this type of technology offers prices very close to zero or even negative in the case of solar photovoltaic due to its practically non-existent variable costs, which makes it worthwhile for the producer to sell its energy at any price. This causes a decrease in the market price and in fact, during this year 2023, there have been many hours where the price has been zero due to the large presence of this type of technology.

- **Hydropower**: This type of technology is very particular because, being renewable and using water as fuel, its behavior in the market is totally different from that of its peers. This is because, unlike solar and wind technologies, which depend entirely on the sun or wind at any given moment, this technology does not depend on water falling from the sky at any given moment, because unlike wind and sunlight, water can be stored and can be used to generate energy at the moment it is desired. However, as can be deduced, this 'storage' of water is limited, so the amount of water available to generate energy is not infinite and will have to be properly managed. The consequence of this is that its behavior in the market will be guided entirely by a concept known as 'opportunity cost'. Simplifying, this concept consists of selling energy at the best possible moment, i.e. when it can be sold at a higher price. This, which seems so simple, makes the operation of this type of technology very difficult, being very difficult to simulate its behavior when trying to predict future prices, which is the purpose of this thesis. Normally, this type of power plant offers its energy in tranches, that is, it offers certain amounts of energy at different prices, and it is common for this technology to determine the market price for this reason.

- **Conventional generation**: This section includes technologies based on fossil fuel generation, such as coal-fired or combined cycle plants (CCGT). This type of technology has both a relatively high fixed cost, since these types of plants are of great magnitude, and a high variable cost, since they require fossil fuel to operate, which is usually expensive to acquire, in addition to other costs such as the costs associated with the CO2 emissions of this type of technology. The great advantage of this type of technology is its flexibility, since it can vary its production very quickly, being able to cover peaks and valleys of electricity production. Due to all this, these technologies are those that usually set the market price, i.e., an offer of this type of technology is usually the last to enter the bidding process, thus setting the break-even point and consequently the price that will be paid to all other technologies that have entered the bidding process.

Below is part of the supply curve of Figure 23 that entered the matching, showing what type of technology occupies each location and what the price of energy was that day at that time.

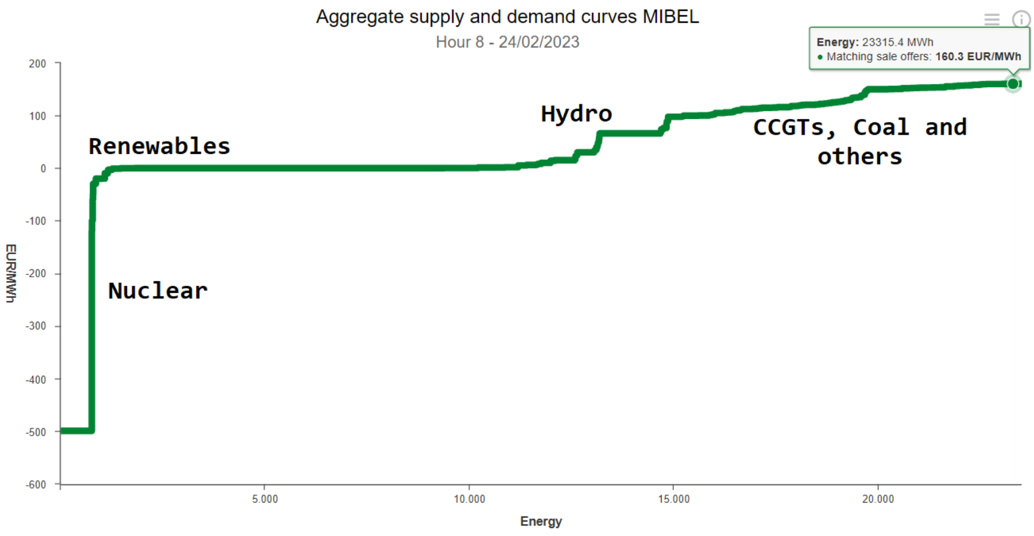


Figure 24: Generation techonologies on the supply curve. Source: OMIE and own

First, the market price that day at that hour was 160.3 EUR/MWh, and it can be assumed, due to its high price, that this offer corresponds to a combined cycle (or hydro) which uses gas to generate electricity. It is necessary to clarify that the offers of the hydropower technologies will extend over the entire curve and will not necessarily be where indicated in the image since, as explained above, this type of technology bases its offer on the opportunity cost, and offers its energy in tranches. On the other hand, renewable and nuclear technologies made the lowest bids as explained above. For this reason, it is of great interest to study how renewable energies can influence the market price, since if they were able to cover all the demand, leaving conventional power plants out of the equation, the price of energy could be greatly affected downwards. Once this is understood, we will proceed to explain the current situation of the day-ahead market in Spain and how renewable energies affect its price formation.

6. Spain Overview

6.1 European Regulatory framework

In order to understand the current situation of the electricity sector and, specifically, of the Spanish electricity market, it is essential to have a thorough knowledge of the current legislation regulating these activities.

First, it is essential to understand the objectives of European policies related to the electricity sector, since these guidelines set the course to be followed by the member countries of the European Union, including Spain. These policies revolve around three objectives, which are represented below:

Figure 25: Three main pillars of the European energy policy. Source: ICAI

For the sake of this thesis, special attention will be paid to the European objective of achieving a single internal market throughout Europe. The key elements of this European objective are as follows:

- It is a strategic instrument to increase competitiveness and consequently market liquidity, since on the one hand consumers have more options when buying energy and on the other hand producers have more opportunities to access the market, especially those smaller producers that invest in renewable energies.

- A framework could be achieved within the EU where the CO2 emissions trading mechanism can function properly, thus facilitating the integration of renewables across Europe.

- This single market would be based on a sufficiently extensive and secure infrastructure of interconnections between countries. This is one of the biggest problems today in achieving this internal market, especially in Spain, since being a peninsula, its possibilities when it comes to interconnecting with other countries are very limited, with Portugal and France being the main countries with which it has a notable interconnection.

- Such a market would contribute significantly to security of supply.

Once the pillars on which EU energy policies revolve are understood, in view of the challenges and difficulties faced by the European electricity system today, such as the growth and integration of renewable technologies, the integration of decentralized energy sources, the active participation of consumers in the market and the necessary development of infrastructures, EU energy policies revolve around the following points:

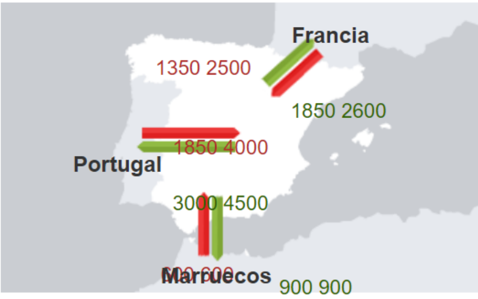
- Continuation with the low-carbon/green policy agenda
- Strengthening European energy market integration
- Predominance of market-based approaches
- Building confidence and trust of consumers in markets
- Reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels
- Increasing the share of renewable energy to, at least, 32% in 2030 (proposal up to 40%)
- Energy saving plans, reaching at least 32.5% of energy savings in 2030
- Reform of the EU Emissions Trading System (ETS)

Currently, the European strategy is driven by the European Green Pact, a package of policy initiatives adopted in 2020, which sets out a detailed vision of how to make Europe the first climate-neutral continent by 2050, safeguarding biodiversity, establishing circular economy practices and eliminating pollution, while boosting the competitiveness of European industry and ensuring a just transition for the regions and workers concerned. Within this pact, one of the most relevant packages of proposals is Fit for 55, which aims to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels.

6.2 International interconnections

Today, the objective of having an internal market with a single price for all member countries of the European Union is still far from being fully achieved, since the fundamental element to achieve it is the interconnection capacity between countries. This is due to the fact that when there is interconnection capacity between two electricity systems, such as the Spanish and French systems, the system where the energy is cheaper exports it to the country where it is more expensive, making the price of energy in the exporting system more expensive and making it cheaper in the importing system (compared to the situation without interconnection). This exchange continues until the transmission line between the two countries (the interconnection) is saturated or when the prices of both systems have equalized.

Regarding the interconnection capacity available in Europe today, it could be said that these interconnections are not being carried out at the expected rate due to the high level of investment involved and the difficult task of sharing the costs of the project, which is one of the pending tasks for many European countries, especially Spain. In this regard, Europe recommended that member countries should have an international interconnection capacity of at least 10% of the electricity generation capacity installed in the system by 2020 and 15% by 2030. Today, Spain's total international interconnection capacity does not exceed 3%, falling far short of the minimum 10% recommended by the EU. This is one of the biggest problems of the Spanish electricity system, since being a peninsula, its interconnection possibilities are very limited. Below is an illustration from REE showing the interconnection capacities, in MW, for commercial use available in July 2023.



Interconnection	Minimum	Maximum
Francia - España	1850	2600
España - Francia	1350	2500
Portugal - España	1850	4000
España - Portugal	3000	4500
Marruecos - España	600	600
España - Marruecos	900	900

Figure 26: Commercial interconnection capacities. Source:[13]

It is necessary to point out that the capacities shown in the image are capacities that remain vacant on the lines for commercial use and are not intended for security of supply. Furthermore, these capacities are not exact, but are forecasts made by the system operator, Red Eléctrica in the case of Spain, of the most probable margins of interchange capacity between systems and represent the combination of the limitations detected by the corresponding operators of both systems. These exchanges between countries, as indicated above, are aimed at increasing competitiveness and equalizing prices throughout Europe, although at the moment this is not possible precisely because of the scarce interconnection capacity.

6.3 Spanish Regulatory Framework

To understand the current situation, we must go back to 1997, when Law 54/1997 on the Electricity Sector was passed on November 27, 1997, which marked the beginning of the process of progressive liberalization of the sector through the establishment of an organized energy trading market, the opening of the networks to third parties and the reduction of public intervention in the management of the system. In this way, the vertical disintegration of the different activities began, segregating the activities under a natural monopoly regime, transmission and distribution, from those carried out under free competition, generation and commercialization. The remuneration of the production activity was based on the organization of a wholesale market, abandoning the principle of cost recognition (cost of service). In the case of the networks, the principle of third-party access to the networks was established, and their remuneration regime would continue to be set administratively, based on the costs of the activity. With this law, the activity of marketing electricity also appeared as an activity independent from the rest of the supply activities, an activity that was provided with a regulatory framework to allow consumers freedom of contracting and choice. Finally, the management of the system was entrusted to commercial and private companies, responsible, respectively, for the economic and technical management of the system.

Under this law, starting in 2004, when renewable energies were still in their initial stage and were not as efficient as they are today, the government launched a plan to promote this type of technology. This was done through a series of incentives and subsidies to install this type of technology, which led to an artificially accelerated growth of the presence of this type of technology in the Spanish electricity system. These incentives can be classified into two types:

- Feed in tariff (FIT): This incentive consisted of providing investors in renewable technologies with a long-term contract that guaranteed them a fixed remuneration for the energy generated by their plant, thus avoiding market risk. This incentive was intended to encourage investment in this type of technology at this early stage.

- Feed in premium: This incentive consists in the fact that the generator sells its energy in the market and receives as remuneration the market price plus a premium. This incentive, unlike the previous one, has the risk of depending on the market price.

It could be said that these incentives fulfilled their function by greatly increasing the presence of renewable technologies in the Spanish electricity system, however, they created a national debt, which increased year after year until 2013, when the reform of the electricity sector was carried out. Below is a graph showing the historical evolution of the national deficit measured in millions of euros:

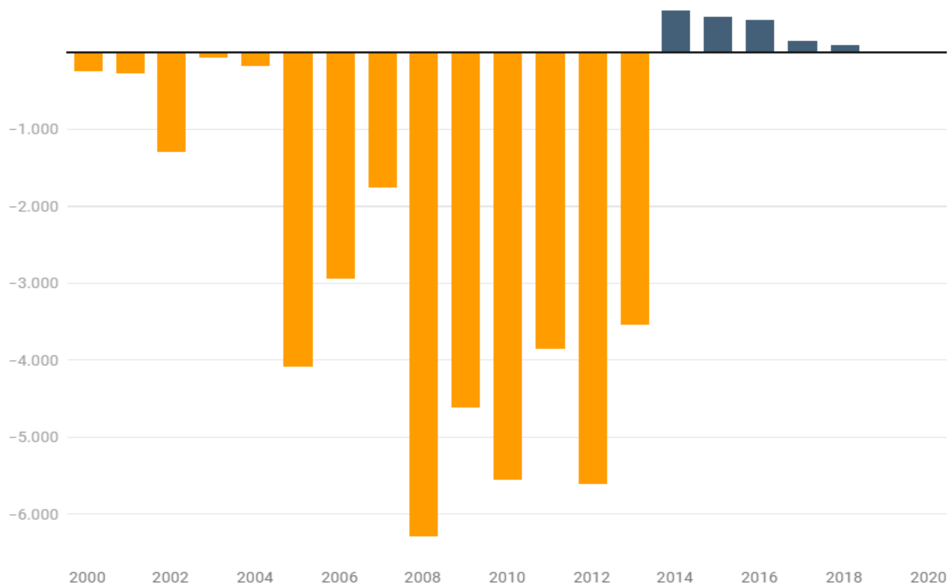


Figure 27: Historical evolution of the national deficit. Source: [14]

Thus, Law 24/2013 was born, which defines its purpose as follows: "The basic purpose of this Law is to establish the regulation of the electricity sector guaranteeing the electricity supply with the necessary levels of quality and at the lowest possible cost, to ensure the economic and financial sustainability of the system and to allow a level of effective competition in the electricity sector, all within the principles of environmental protection of a modern society". From this moment on, due to the delicate financial stability in which the electricity sector had ended up due to its debt, it was forbidden by law to have a deficit that would increase the debt as can be seen in the graph above where the situation is completely reversed in 2014, where there starts to be a surplus to be able to recover the debt that had been accumulating during the previous years. In addition, with this law the tariffs for consumers were changed and the incentives for renewables were oriented towards the market.

6.4 Current structure of the sector

This section will explain the current situation of the Spanish electricity sector regarding the presence of the different generation technologies and their effect on the market price.

First, the historical evolution of the installed power of the different generation technologies, in MW, since 2019 is shown in order to understand the magnitude of the Spanish electricity system as a whole:

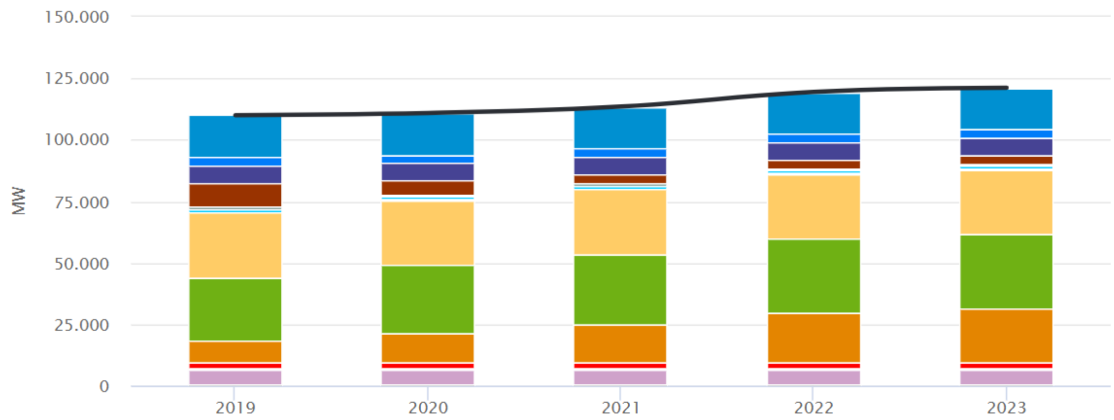


Figure 28: Evolution of the installed power of different generation technologies since 2019 in Spain. Source: [15]

As can be seen in the graph, the total installed capacity has been progressively increasing to reach 121 GW of installed generation capacity at present. It can also be seen how this total power is made up of many different technologies represented by colors, with wind and combined cycle currently being the technologies with the highest installed power. Next, as we are not interested in all the generation sources represented in the color bars, the evolution of those considered most important for this thesis is shown, being wind, solar photovoltaic, nuclear, combined cycle and coal generation technologies the most relevant energy sources:

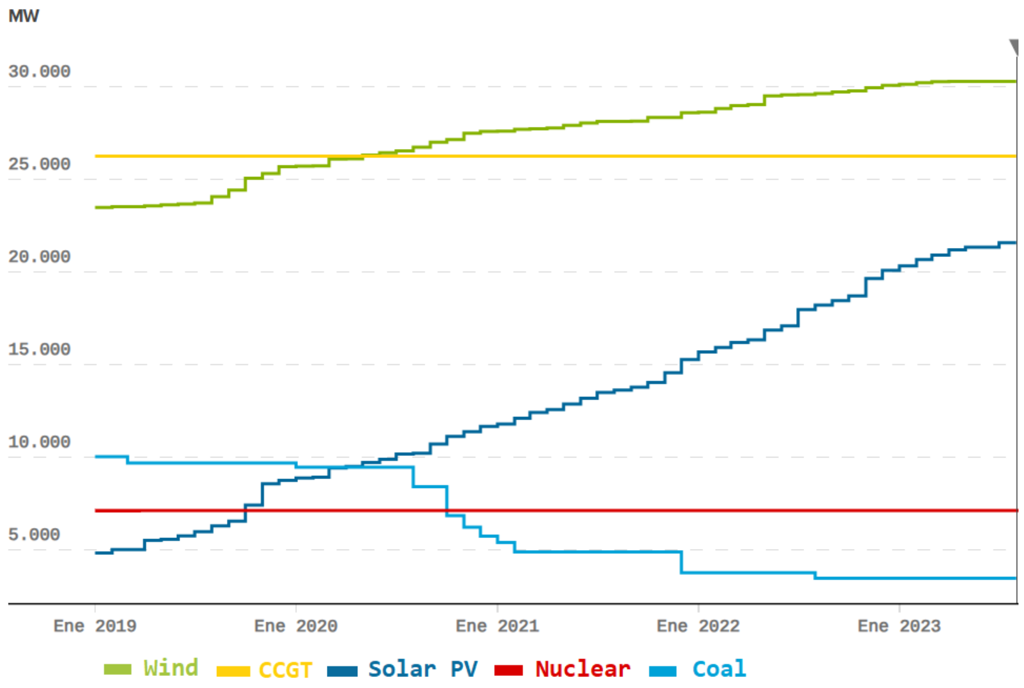


Figure 29: Evolution of the most relevant installed power generation technologies. Source: [16]

As can be clearly seen in the image, the trend of renewables is increasing while nuclear and combined cycle technologies remain stable during all these years. On the other hand, it is worth highlighting the fall of coal installed capacity, decreasing from 2017 to the present day by almost 65%. This technology, due to its high CO2 emissions has its years numbered in practically all European countries, especially in Spain, where generating energy with this technology has never been cheap due to the poor quality of national coal and the need to import it in many cases.

After knowing the current situation, it is not easy to predict what will happen in the coming years, although the Government sets out its vision in a document called the National Integrated Energy and Climate Plan (PNIEC), written in 2019 (and currently pending updating), which sets out a series of objectives to be achieved in different aspects such as installed capacity according to technologies or greenhouse gas emissions. Below is a table showing the targets in terms of installed capacity [in MW] of the technologies mentioned above up to 2030.

Year	2025	2030
Wind	40633	50333
Solar PV	21713	39181
Coal	2165	0
CCGT	26612	26612
Nuclear	7400	3181

Table 1: PNIEC installed capacity objectives

As mentioned above, this document is pending a necessary revision, since the growth of renewable energies, especially solar photovoltaic, is being much higher than expected, so the revision to be made is upwards. It is necessary to clarify that the data of installed solar photovoltaic power, in addition to taking into account the large solar installations, also takes into account self-consumption, which due to the unexpected and sharp increase in the price of electricity in recent years is growing at unsuspected levels since people's reaction to the very high prices that have been presented has been to want to hedge against market risk.

6.5 Day-ahead market situation

Once the situation of the sector is known, we will explain how these technologies influence the market and how the market has behaved historically. The historical evolution of the annual arithmetic average of the Spanish day-ahead market (MIBEL) price is shown below:

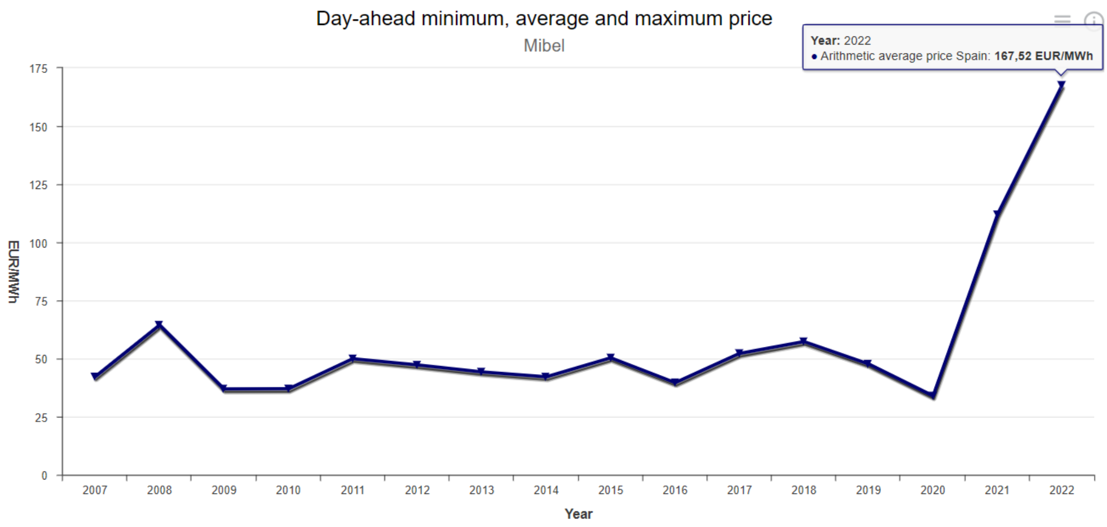


Figure 30: Evolution of the annual arithmetic average of the Spanish day-ahead market price. Source: OMIE

As can be seen in the image, the price of electricity in the day-ahead market has historically been relatively stable, varying from a minimum of 36 euros to a maximum of 64 euros. This situation ends in 2020, where paradoxically a minimum average price of 34 euros is reached and then increases uncontrollably to 167.5 euros/MWh reached in 2022. This situation has arisen due to the sudden and unexpected increase in the price of gas, since the power plants that use this fuel, the Combined Gas Cycles (CCGTs), are the ones that generally determine the price of energy and this increase in the cost of fuel has led to a proportional increase in their bids in the market. The reliance on this technology is due to over-investment in the past, as it was considered to have several advantages over other options. Some of these advantages are listed below.

- Flexibility: These types of power plants can 'quickly' adjust their electricity generation to meet demand. As mentioned above, due to the physical conditions of electricity, this feature is of great value.
- Efficiency: This type of technology is more efficient than other technologies such as coal, which is attractive to investors from an economic and environmental point of view.

- Pollution: Emissions from these plants are lower than those of conventional thermal power plants.
- Installation: This type of power plant has a relatively low investment cost per MW installed, the construction period is not excessively long and compared to conventional thermal power plants, they need less surface area per MW installed.

As stated throughout this thesis, this technology that usually determines the price of energy could be left out of the Spanish energy mix if there is enough renewable capacity to cover all demand. In order to assess this hypothesis, two graphs illustrating the absolute monthly generation of wind and solar PV in the period from 2018 to 2021 are shown below.

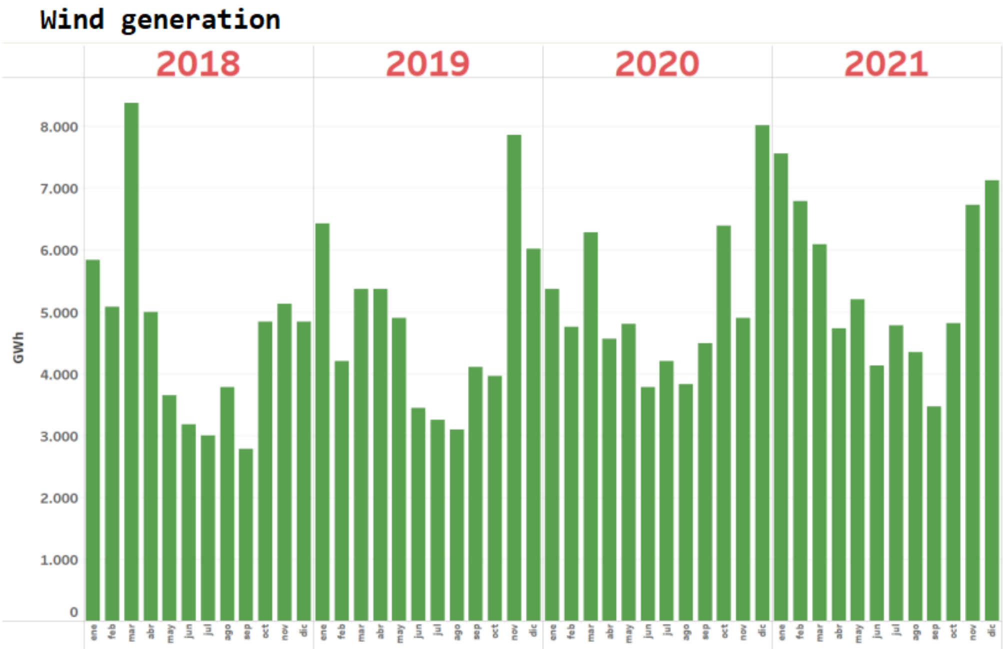


Figure 31: Monthly wind power generation, 2018-2021. Source: [17]

It can be clearly seen how wind generation is seasonal, reaching its maximums in the first and last months of the year while the minimums are reached in the hottest months. Furthermore, this seasonality is very marked, with the maximum value reached being greater than twice the annual minimum in all years.

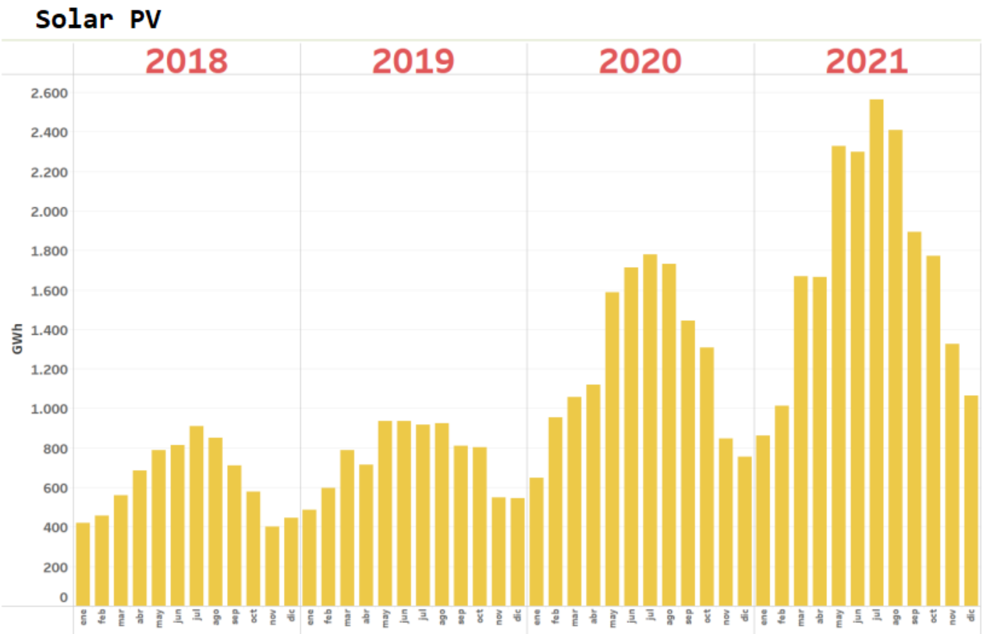


Figure 32: Monthly Solar PV power generation, 2018-2021. Source: [17]

As with wind generation, in this case there is also a very clear seasonality, this time being the hottest months where this technology reaches its maximum generation. Something to note is how the difference between maximums and minimums increases with installed power as can be seen in 2021, where total generation is much higher than in 2018.

The most important conclusion that can be deduced from these two graphs is that solar and wind technologies are seasonally complementary, since one generates its maximums in the coldest months and the other in the hottest months. Moreover, this complementarity does not only manifest itself during the months of the year, as it occurs on a daily basis, as can be seen in the following figure:

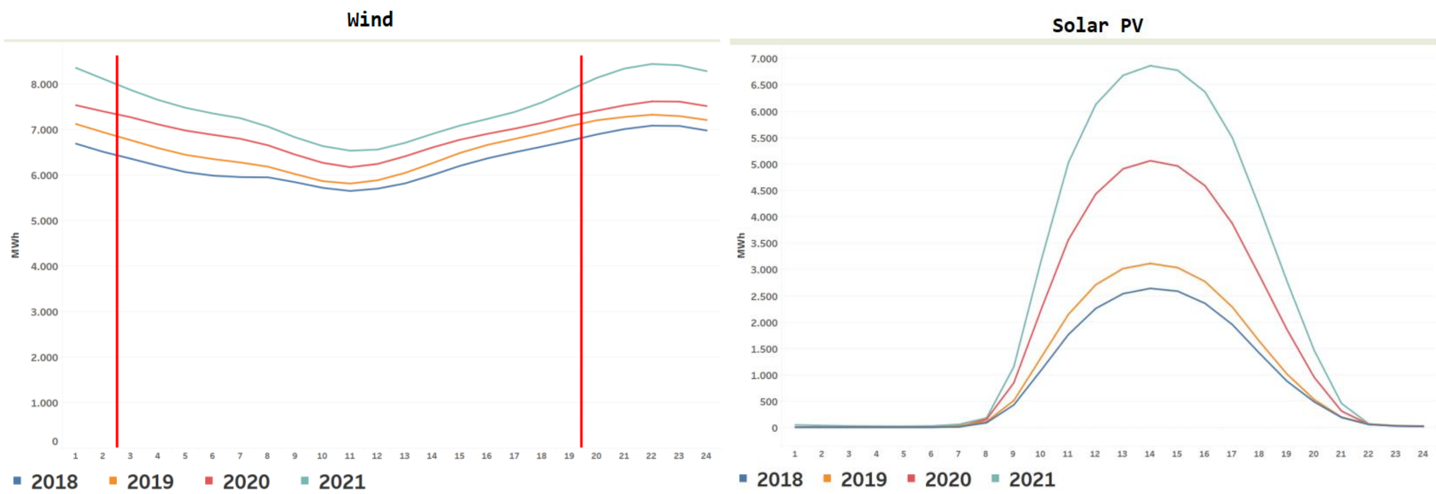


Figure 33: Daily wind and Solar PV power generation by hours, 2018-2021. Source: [17]

This difference in hourly generation is very noticeable in solar technology, which concentrates all its generation in the central hours of the day, being this the time when wind reaches its minimum.

This complementarity, both seasonal and hourly, could make it possible for these two technologies to cover a large part of the demand, greatly reducing market prices. To confirm that this price reduction would occur, below is a figure showing the prices at which solar and wind technologies offer their energy in the market.

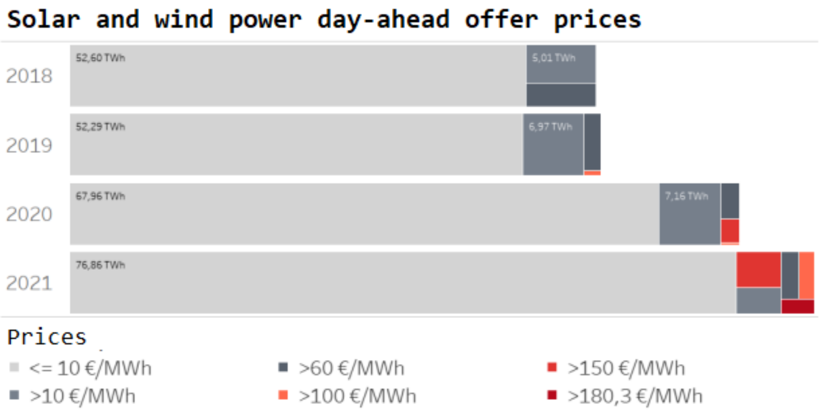


Figure 34: Solar PV and Wind power Day-Ahead Market bid prices. Source: [17]

It can be clearly seen that the vast majority of prices at which these types of technologies offer their energy are less than 10 EUR/MWh, which confirms this decrease in the price that both solar and wind energy would cause if they were able to cover the entire demand. It can also be seen that over the years, although a minority, offers at a very high price (>100 EUR/MWh) are more present. This type of strategy arises from the opportunity cost of technologies such as wind power, whose generation is more unpredictable than solar. In other words, wind energy producers have to assess how likely it is that their generation forecasts will be fulfilled, because if they are not, and consequently they cannot generate the energy that has already been sold, they would be obliged to buy the energy they have sold in one of the existing intraday markets, which could lead to large losses. For this reason, they bid at a relatively high price, since in the event of selling that energy and then not being able to produce it, they could buy it in one of the intraday markets without losing too much money or even gaining it.

Once the current global, European and Spanish situation is understood, the study will be carried out by analyzing the impact that renewables will have on the day-ahead market price in 2025. For this purpose, an existing prediction model will be used to carry out a sensitivity study, among other things, as explained below.

7. Study of the impact of renewable technologies on energy prices in 2025

This section will use all of the above to study the impact that renewable energies will have on the day-ahead market in 2025. To conduct this study, an established forecasting model that is commonly used to predict the long-term day-ahead market price will be used. This model, which will be explained in detail below, uses a combination of historical data, weather patterns and other variables to generate electricity price forecasts. By applying this forecasting model to the context of renewable energy, we can get an idea of the potential impact of this energy source on the electricity market in 2025.

7.1 Forecasting Model

The prediction model used for the thesis is called xPryce and the company that developed it is SIMULYDE. This model is formulated as an optimization problem, programmed in GAMS/CPLEX, and simulates the matching of the day-ahead MIBEL market and France. The modeling takes into account both the technical constraints associated with the different production technologies and the market structure and its regulation.

In short, xPryce uses the following as input variables:

- Hourly demand for all years of the time horizon
- Generation technologies, with their corresponding technical characteristics, production profiles and installed capacities for each year
- Monthly commodity prices for the entire execution time horizon
- Interconnection capacity with France, Morocco, Andorra and the Balearic Islands and interconnection capacity with Italy, Belgium, Switzerland, Germany and Great Britain to predict how the French market will behave.

Some of this information can be modified by the user, while other information is intrinsic to the modeling and cannot be modified. In the case of this thesis, the installed solar and wind power parameters will be modified in addition to the gas price, keeping all other parameters constant. The model works with the different generation technologies that exist in the MIBEL and France, taking into account the technical characteristics and particularities of each of them. The different installed capacities, in MW, of the technologies that will remain constant when analyzing the impact of renewable energies on the day-ahead market price in 2025, i.e. all except solar photovoltaic and wind, will be shown below.

Technology	Solar Thermal	Nuclear	Coal	CCGT	Cogeneration	Hydropower	Pumping turbination
Installed Power[MW]	2500	7117	0	24627	5066	14788	3331

Table 2: Installed capacity of generation technologies

In the same way, the different interconnection capacities used by the model in the case of Spain are shown below:

Interconnection	France -> Spain	Spain -> France	Portugal -> Spain	Spain -> Portugal
Capacity [MW]	2800	2800	9000	9900

Table 3: International interconnection capacities

Once the characteristics of the model are known, we will proceed to explain the methodology to be used to carry out the analysis.

7.2 Methodology

A sensitivity study/analysis will be conducted to examine the influence of renewable energies on energy prices in 2025. In this type of analysis, different input parameters (wind power installed, solar PV power installed…) are systematically modified within a specified interval, while keeping other parameters constant, to observe the corresponding changes in the output. By this, it is possible to understand how each parameter affects the system's behavior, in this case, the price of energy in the day ahead market. Being a study that aims to know how renewable technologies will affect the price of energy in the day-ahead market, it has been decided to study the scenarios where the installed capacity of solar and wind generation varies. These scenarios have been replicated in different cases where the price of gas has been modified, thus being able to check how renewable technologies affect the price of the electricity market depending on the price of gas. It should be noted that both the MIBGAS price and the TTF will be modified, since, in addition to being empirically closely related, modifying only the MIBGAS forecasts without modifying the TTF could lead to confusing results due to the influence this would have on imports and exports of the Spanish electricity system.

From now on, the term "scenario" will denote a specific configuration of solar and wind capacity installed within the system. Conversely, the term "case" will represent a particular gas price condition. Within a case, which could be, for example, where the gas price increases by 1 €/MWh compared to the base case that will be defined just after this, many scenarios will be simulated where the capacities of renewable technologies installed in the system will be modified.

The study will start by establishing a base case and a base scenario, in which the most likely parameters for the year 2025 will be defined. These parameters have been chosen based on the PNIEC, as well as on estimates made by Invesyde, the company that provided me with this price forecasting model. It should be noted that, as explained above, the model only allows input of installed capacity at the end of each year. Despite this, the prediction model does not consider that there will be the same installed capacity throughout the year, but assumes a constant growth per month from the capacity established in year n-1 (which would be the installed capacity at the end of that year) to the capacity established in year n, in this case 2025. A table with the input data established for the base case and base scenario is shown below:

	TTF [€/MWh]	MIBGAS [€/MWh]	PV capacity [MW]	Wind capacity [MW]
2025-01	46,270	43,408	28 691	37 506
2025-02	44,148	41,417	29 146	37 674
2025-03	41,601	39,027	29 600	37 842
2025-04	40,752	38,231	30 055	38 011
2025-05	40,327	37,833	30 509	38 179
2025-06	39,478	37,036	30 964	38 347
2025-07	39,903	37,434	31 418	38 515
2025-08	39,478	37,036	31 873	38 683
2025-09	41,601	39,027	32 327	38 851
2025-10	43,299	40,620	32 782	39 020
2025-11	44,148	41,417	33 236	39 188
2025-12	45,421	42,611	33 691	39 356

Table 4: Parameters for the base case and base scenario

Once the parameters that establish the base scenario and the base case are known, in order to analyze how renewables influence the price of the day-ahead energy market, simulations will be made of different cases in which the parameters that establish the price of gas in MIBGAS and TTF will be modified, and different scenarios in which the installed solar photovoltaic power and installed wind power will be modified, keeping others constant, such as, for example, demand or interconnection capacity.

The input data for installed PV and wind power will be adjusted in intervals of 0.5 GW up to 3 GW above and below the values specified in the base case for each respective technology. In each scenario, the installed power will be adjusted both in year n and year n-1, aiming to thoroughly assess the influence these technologies exert on the market price. This approach allows for a more comprehensive examination of the impact these technologies have on the market dynamics. When making the visual representations of the results of the sensitivity study, the value of the base scenario for each technology will be represented with the number 0, i.e., in the sensitivity matrices, the value 0 will mean that the model has used as input the renewable installed capacity values shown in the table above. As for gas, it has been decided to study the cases in which the price rises in MIBGAS and TTF with respect to the expected: 1 €/MWh, 5 €/MWh and double, the latter replicating an unexpected geopolitical situation such as the war in Ukraine. The reason for modifying both values is explained in the sensitivity study section above.

The following table shows the scenarios and cases that will be studied:

Solar PV and Wind power installed [Δ GW]													Gas price[Δ€/MWh]			
-3	-2,5	-2	-1,5	-1	-0,5	0	0,5	1	1,5	2	2,5	3	0	1	5	Double

Table 5: Variation in installed capacity and gas prices

Once the different cases and scenarios that will be studied in the first instance are clear, we will proceed to explain what type of analysis will be carried out. First, the base case and base scenario will be studied in detail, since it is the most probable case and therefore the one of greatest interest in this thesis. Once the results of the base case and the base scenario have been obtained and represented, the model will be run by changing the values of installed solar PV and wind power, i.e. changing the scenario and keeping gas prices constant, i.e. within the same case. In this way, a matrix will be constructed where it will be possible to see how the price varies according to these parameters and thus be able to compare the data with the base scenario, being able to check how renewables influence the day-ahead market price.

These types of analysis will be performed on a case-by-case basis:

- Comparison of annual average day-ahead market prices as a function of the installed power of solar photovoltaic and wind technologies using a two-dimensional matrix and a three-dimensional graph to be able to study the slopes formed by the points representing the annual average price of each scenario.
- Comparison of the average monthly prices of the most relevant scenarios: A graph will be made where the monthly day-ahead market prices of the most relevant scenarios will be superimposed.
- Capture price study: In the same way that the annual prices of the different scenarios indicated were represented, the solar and wind capture prices will be represented to study the remuneration of these technologies.
- Study of the economic viability of the different technologies: With the calculated capture price, the remuneration expected for each technology will be calculated and compared with its LCOE respectively to check the viability of these installations according to the scenario.

Once the methodology to be used in the study is known, the analyses indicated above will be carried out. Microsoft Excel and MATLAB were used for the representation of the results obtained and their analysis.

7.3 Analysis of the base case and base scenario

First, the base case and the base scenario will be studied in detail, i.e., the situation where the input data to define the solar and PV installed capacity are the most probable for 2025, as well as the gas price in MIBGAS and TTF will be studied. The input data can be seen above (Table 4).

By running the model with the parameters indicated in the table, the following monthly average prices in the day-ahead market are obtained:

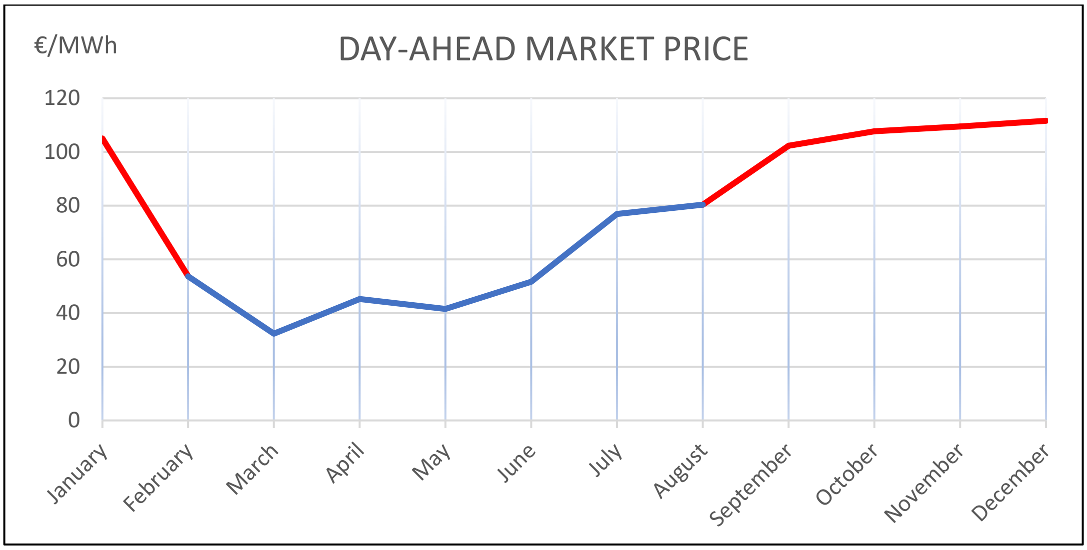


Figure 35: Average monthly prices for the base case and the base scenario in 2025. Source: Own elaboration

The months in which it has been necessary to use combined cycle power plants to supply demand are shown in red. As can be seen, this coincides with the months when energy is most expensive, which is a clear indicator that the presence of this technology in the mix makes energy more expensive. It can also be seen how in the central months of the year, where demand is lower and renewable energy is able to generate more energy, the price reaches the lowest values of the year, reaching 32.3 €/MWh in March. In order to compare it with the current situation, below is a graph showing this price forecast for 2025 together with the monthly prices for 2021 and 2022.

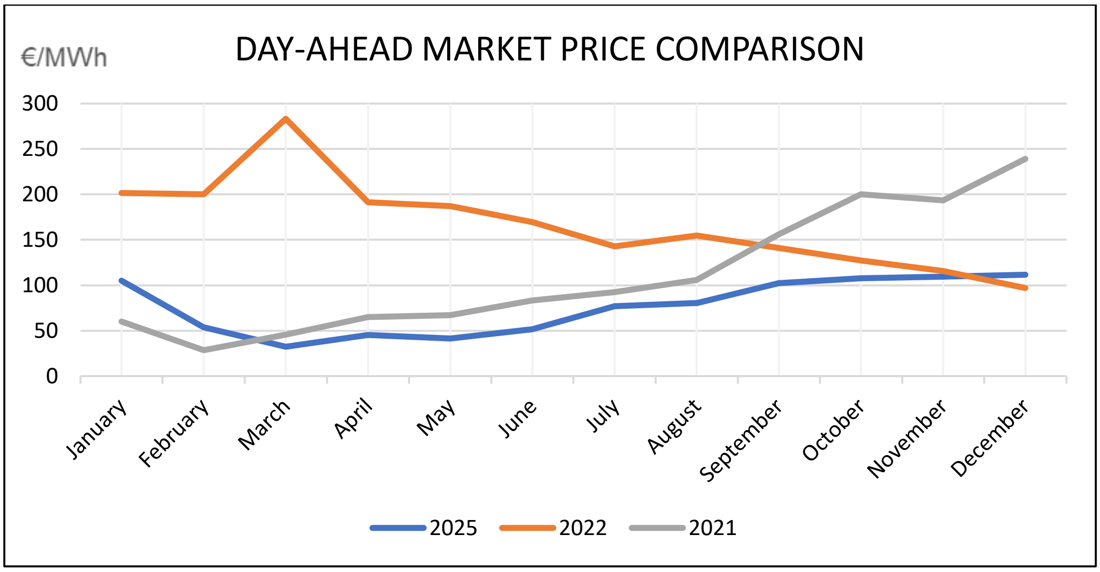


Figure 36: Comparison of the average monthly prices in 2025 (base case), 2022 and 2021. Source: Own elaboration

These price differences are due to many factors such as demand, the price of fossil fuels or the price of CO2 certificates. However, one of the most relevant factors is the increase in installed renewable power, which clearly has a lowering effect on the day-ahead market price. This could be called into question by looking at the 2021 chart, which even reaches lower values than the 2025 chart in both January and February. Much of this is due to the exceptionally low gas prices during those dates, reaching below 16 EUR/MWh in MIBGAS on some days in February 2021, where the average day-ahead market price reaches its minimum. In comparison, for this 2025 base case, a price of approximately 41 EUR/MWh in MIBGAS in February has been used, so the difference between day-ahead market prices could have been much higher in the absence of higher installed renewable capacity.

In order to analyze the generation of the different technologies throughout the year and how it affects the price in detail, Spain's electricity generation mix in 2025 has been represented below on a monthly basis.

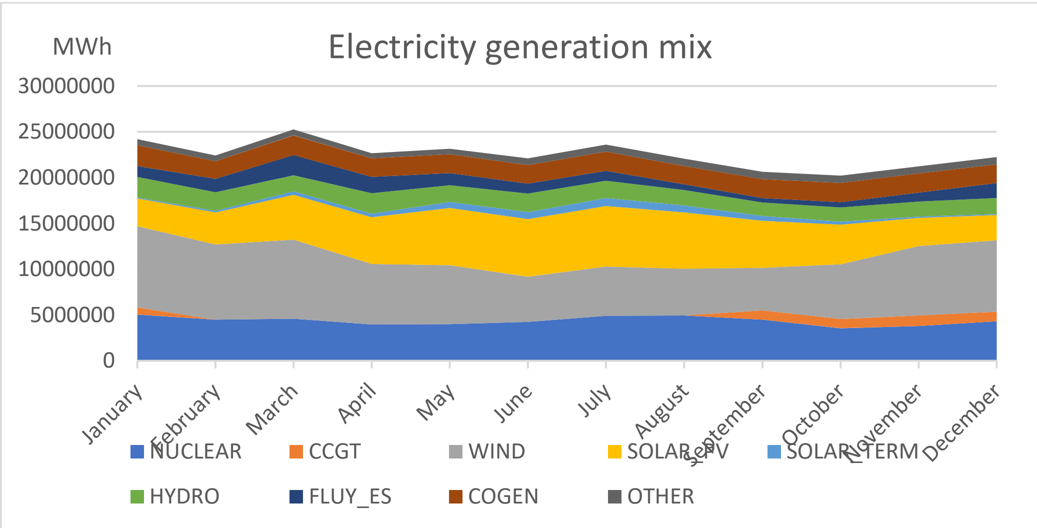


Figure 37: Electricity generation mix in 2025 for the base case. Source: Own elaboration

It can be seen how clearly wind and solar photovoltaic energies together would have the greatest presence in the mix, leaving out combined cycle plants in the central months of the year. Moreover, the complementary nature of these two technologies, as described in the section on Spain's energy context, is noticeable. Wind energy prevails during the colder months, while solar energy takes the lead during the hotter months. Knowing this, it has been decided to represent the monthly market price together with the sum of photovoltaic and wind generation.

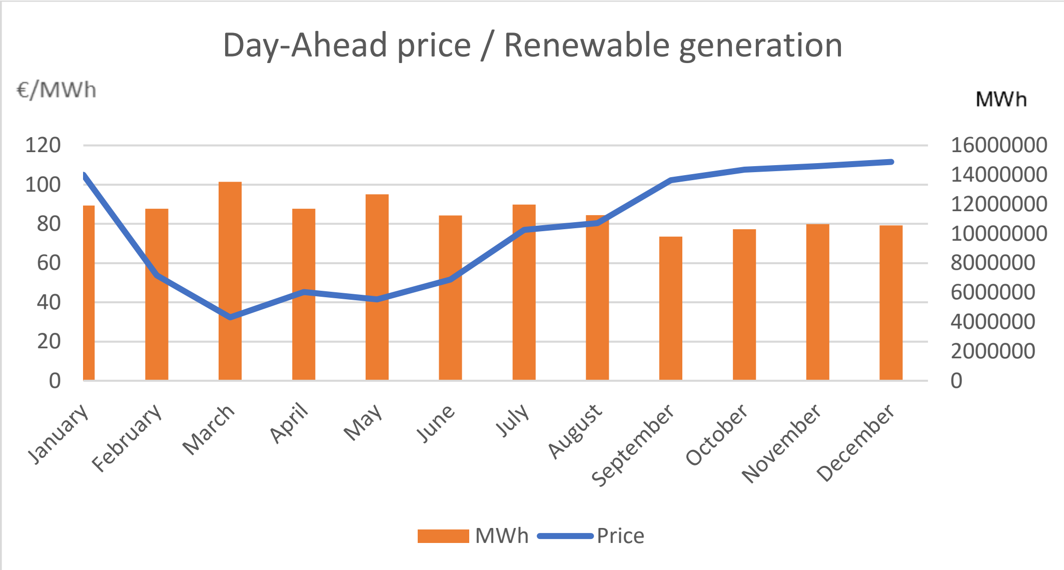


Figure 38: Comparison of the monthly market price in 2025 with renewable generation for the base case. Source: Own elaboration

As can be seen from these results, there is an inverse relationship between the installed renewable power and the market price, i.e., the more renewable generation, the lower the market price. It should be noted that this rule is not entirely accurate, since other factors such as demand or the interconnections have a significant influence on the final price as can be seen in the month of February, for example, where there is less renewable generation than in January and yet the average annual price is much lower. This is largely due to the reduction in demand that allows the disappearance of the CCGT technology from the energy mix as can be seen in the figure 37.

7.3.1 Sensitivity analysis

From now on, the gas price used to make the predictions will continue to be the one indicated in table 4, however, the values of solar and wind power installed capacity will be modified as indicated in the methodology. In this way, the sensitivity matrix will be obtained, which indicates how the price will behave as a function of the installed capacity of renewable energies. This matrix shows the average annual prices for each scenario studied. The way in which it has been decided to make this matrix is with a differentiation by colors where the dark blue would be the minimum annual average price reached and the dark red would be the maximum. The price indicated by each color can be consulted in the sidebar and in the annex where the results of all the simulations can be found. The axes of the matrix indicate the variation in the installed capacity of solar and wind power technology with respect to the base scenario.

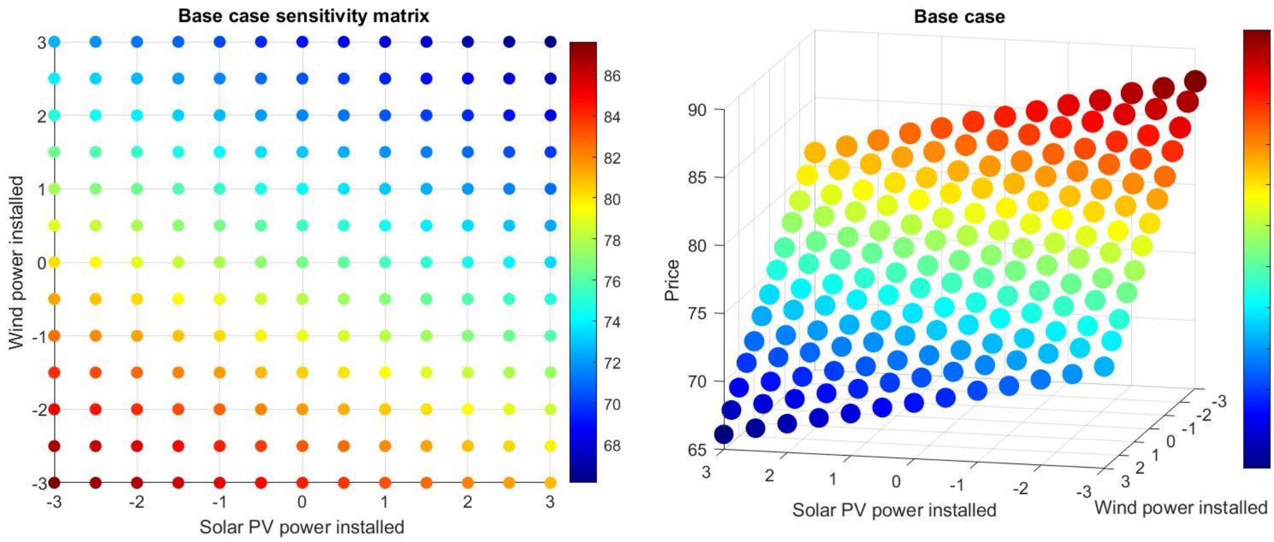


Figure 39: Base case sensitivity matrix, 2D and 3D. Source: Own elaboration

It can be observed that the minimum price in this case is approximately 66 €/MWh and the maximum price is 87.6 €/MWh. The conclusions that can be drawn from these results are that:

- The difference between the maximum price, which is obtained in the most pessimistic scenario, i.e., when three GW less solar and wind power are installed with respect to the base scenario, and the best scenario, i.e., when 3 GW more solar and wind power are installed with respect to the base case, is: 87.6 – 66 = 21.6 €/MWh.

- The increase in wind generation capacity reduces the average annual price to a greater extent than the increase in solar. This can be clearly seen in the matrices and is illustrated in the following three scenarios:

Solar PV [Δ GW]	Wind [Δ GW]	Annual Price [€/MWh]
Base (0)	Base (0)	76,67
Base (0)	+3	69,13
+3	Base (0)	73,46
Base (0)	-3	84,3
-3	Base (0)	80,09

Table 6: Annual Price of several scenarios

- The table above also shows that the variation in installed wind power has a greater influence on both reducing and increasing the price.

- Based on the three-dimensional representation, it can be seen that the surface obtained by representing the points that indicate the average annual price in each scenario is a perfect plane, where the slopes of the straight line that joins the points of one or the other technology are constant regardless of the situation of the other technology. From this it can be concluded that the increase or decrease that a change in the installed power of any of the technologies produces in the price is independent of the other technology, so that, if this is repeated in the cases where gas increases in price, a simplified but more extensive analysis could be made.

Once this analysis has been done with the annual average prices, the monthly average prices of the most relevant cases will be represented in the same graph.

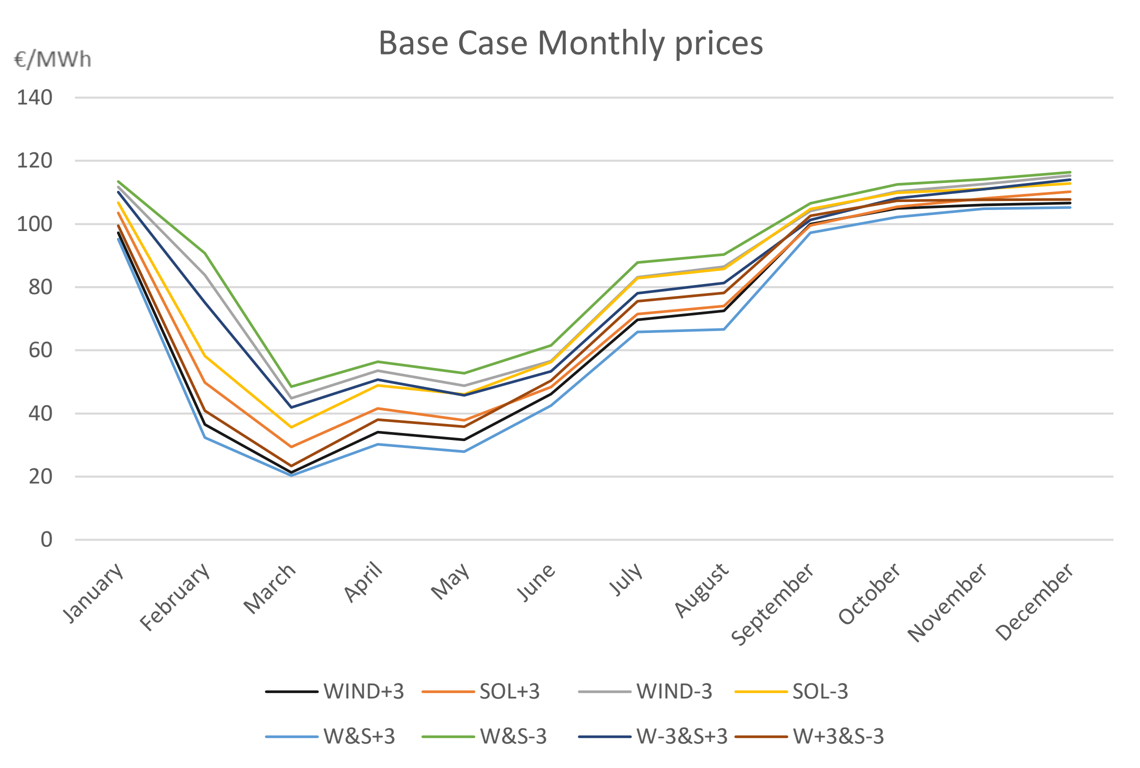


Figure 40: Monthly day-ahead market prices in 2025 for the base case depending on the scenario. Source: Own elaboration

It can be seen how the curves tend to separate in the spring and summer months, while in autumn and winter there tend to be smaller differences. If we compare the most extreme scenarios, i.e., the scenario in which more renewable is installed and the scenario in which less is installed, we can see the following:

	Wind +3 & Solar +3	Wind -3 & Solar -3
Maximum price	105,2 (December)	116,4 (December)
Minimum price	20,3 (March)	48,5 (March)
Spread	84,9	67,9

Table 7: Maximum and minimum price of the extreme scenarios

This shows that the case in which more renewables are installed, despite obtaining a lower price during the year, as expected, compared to the more 'pessimistic' case, the difference obtained between the maximum price reached during the year and the minimum is greater in this case. This shows that price stability is significantly affected by the integration of renewables into the system. A priori, this could be understood as something negative, but due to the situation in which we find ourselves, where the entry of storage technologies could be differential, this type of price signals could be of great interest for investors in this type of technology.

7.3.2 Capture Ratios analysis

Once these analyses have been carried out, we will proceed to use the information gathered and the results obtained to check which scenarios are attractive for investors in solar and wind technology. This will be done by comparing the average annual price captured by each technology with their respective LCOE.

This LCOE is not a fixed and invariable number, but depends on many factors such as the location of the installation or the price of the materials needed, at that particular time, for its construction. For this reason, an average price obtained through a range given by the French investment bank *Lazard*, which published its annual report on the levelized cost of energy (LCOE) in April this year (2023), will be used. Something that stands out in the report is that this is the first time in history that the average renewables LCOE have increased with respect to the previous year, although it should be noted that this is due to the fact that the price range has increased greatly, with the minimum price for this year being the historical minimum for both solar and wind, and the maximum has increased notably.

Among the reasons for the increase in LCOE are inflation, supply chain problems, rising material and logistics prices, as well as higher financing costs with rising interest rates. The following are the results obtained in the report referring to the historical evolution of the LCOE of solar and wind technologies:

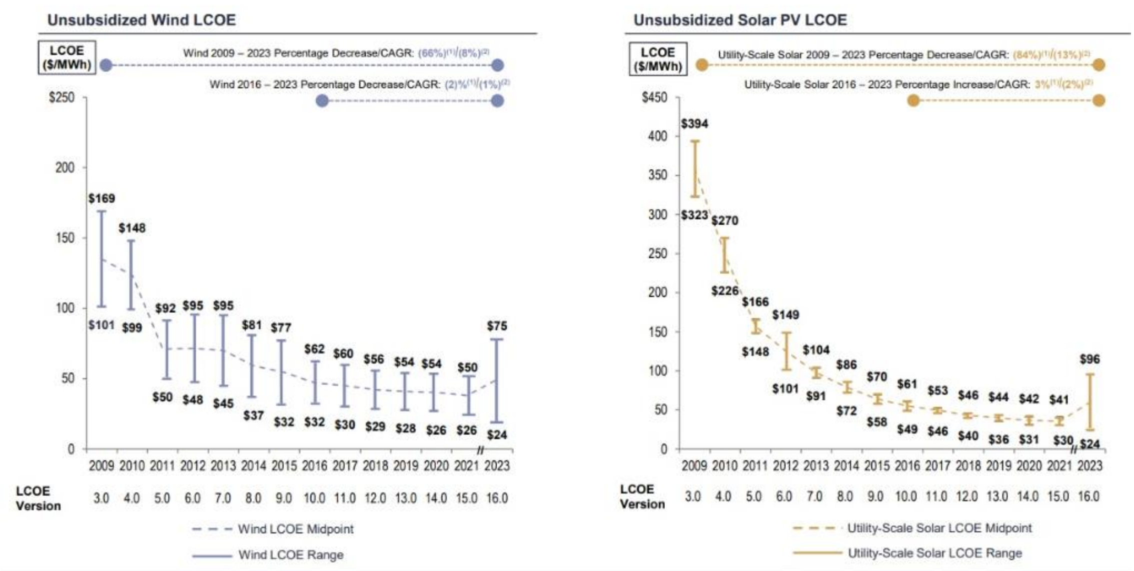


Figure 41: LCOE evolution of wind and solar photovoltaic energy. Source: [18]

For the sake of the thesis, the last two average LCOE values of each technology will be used due to the sudden and probably exceptional increase in the last year. Since these values are in dollars, the following conversion factor: (1$ = 0,92€) will be used to obtain the equivalent in euros.

Solar PV:

$$LCOE\ 2021 = \frac{41 + 30}{2} = 35{,}5\ {}^{\$}/_{MWh} = 32{,}5\ {}^{€}/_{MWh}$$

$$LCOE\ 2023 = \frac{96 + 24}{2} = 60\ {}^{\$}/_{MWh} = 55\ {}^{€}/_{MWh}$$

Wind:

$$LCOE\ 2021 = \frac{50 + 26}{2} = 38\ {}^{\$}/_{MWh} = 34{,}8\ {}^{€}/_{MWh}$$

$$LCOE\ 2023 = \frac{75 + 24}{2} = 49{,}5\ {}^{\$}/_{MWh} = 45{,}4\ {}^{€}/_{MWh}$$

Once these data have been obtained, the capture ratio of each technology is represented. This value indicates what percentage of the average annual price the technology would receive. That is, if, for example, the average annual market price has been 80 €/MWh and the capture ratio of the wind technology has been 0.8, the owner of a wind farm will receive approximately: $80 * 0.8 = 64\ €/\mathrm{MWh}$. In other words, on average, he will receive 64 € for each MWh produced by his wind turbine that year. For this case, these are the results obtained:

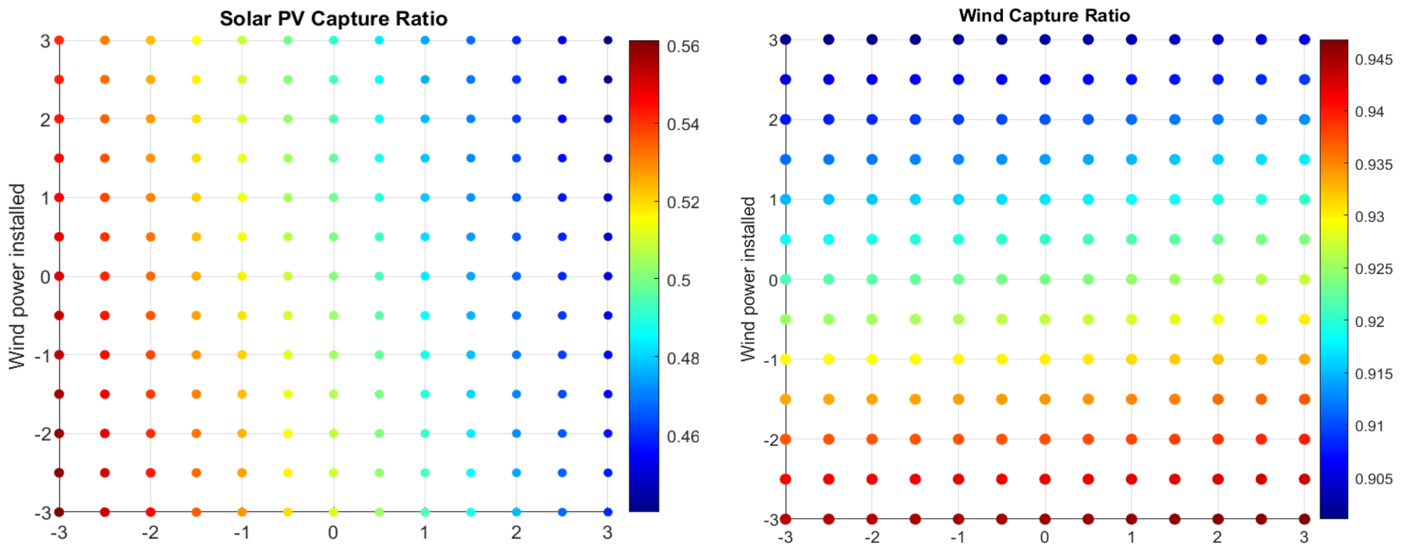


Figure 42: Solar PV and wind power capture ratios for the base case. Source: Own elaboration

To refer to specific scenarios, the following nomenclature is used: (Solar PV power installed, Wind power installed).

The conclusions that can be drawn from looking at these two graphs are as follows:

1. The difference between the maximum and minimum ratio is clearly greater in the case of solar technology, so that the percentage of market price that the solar PV producer

would receive will be affected to a greater extent by the integration of renewable energies into the electricity system than wind energy.

2. The capture ratio of solar technology is much lower than wind in all scenarios, so the average annual wind revenue per MWh generated, in all scenarios, will be higher than that of solar.

3. Peaks and troughs in each technology occur in different scenarios:
   a. In the case of solar the highest capture ratio is obtained in the case where the least renewable technologies are installed (-3,-3) and the lowest in the case where the most renewable capacity is installed (3,3). This is because, if there is not enough renewable capacity installed to cover the demand, it will be necessary to generate energy with conventional generation technologies more hours per year, which raises the price and due to the market model (marginalist), solar technology in many hours could receive a "high" remuneration. Similarly, if there is more renewable power installed, more hours of demand can be covered with this type of technology, which will lower the price and consequently reduce the remuneration of this technology. This phenomenon is known as cannibalization and will be explained later.

   b. The case of wind is more particular, since as can be seen in the image, the highest capture ratio appears when solar technology is at its maximum increase and wind at its minimum (3,-3). In other words, as strange as it may seem, the increase in solar power installed in the system "benefits" the owners of wind turbines when it comes to obtaining a higher percentage of the market price, although this does not necessarily mean that they receive higher revenues per MWh generated on average, as will be seen in the next section. On the other hand, the smallest ratio is obtained at point (-3,3). It should be noted that, looking at the matrix of the ratios captured by wind power, it can be clearly observed how the increase in installed capacity of wind technology affects its ratio very negatively.

7.3.3 Capture Price Analysis

Once the ratios are known, it is sufficient to multiply them by the average prices obtained to obtain the average annual capture price for each technology in each scenario. Once these values have been obtained, they simply need to be compared with the respective LCOE to check whether an investor will be able to amortize its installation (at least that year). The following shows, first, the capture price of each technology, and secondly, the scenarios where this price exceeds its respective LCOE, which will be shown in green while the scenarios where it is not exceeded will be shown in red.

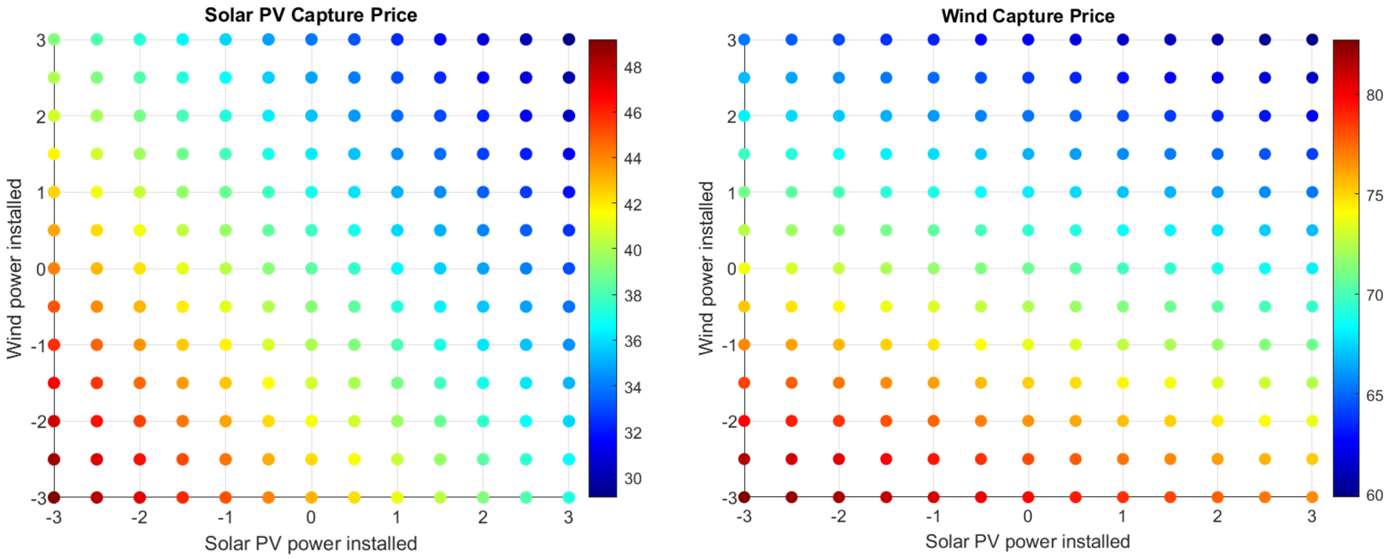


Figure 43: Solar PV and wind power capture ratios for the base case. Source: Own elaboration

Comparing these two graphs with the capture ratios, we can see that although they look very similar, they are not exactly the same. For example, in the case of the capture prices for wind energy, the minimum price is found in the scenario (3,3) while the minimum ratio is found in the scenario (-3,3). From this it can be deduced that, despite being able to think a priori that the worst possible situation for wind is the one in which the minimum possible solar capacity is installed, the reality is that, speaking in absolute terms, the worst possible situation for wind turbine investors is the one in which the highest possible renewable capacity is installed.

It can be clearly seen how the remuneration of solar technology in all scenarios is lower than that of wind power, as could be deduced by studying the ratios captured, so the maximum and minimum prices captured for the technologies are shown below in order to study them in more detail.

	Solar PV Price	Wind Price	Difference
Maximum	49,2	82,7	33,5
Minimum	29,1	60	30,9
Spread	20,1	22,7	-

Table 8: Maximum and minimum capture prices for each technology

It should be noted that the maximum prices have been obtained in the scenario (-3,-3) and the minimum prices in the scenario (3,3) for both technologies. Thus, it is clearly observed that the greater integration of renewables leads to lower remuneration for them. This is known as cannibalization and is a risk that investors run and that will increase year after year.

Specifically, one of the most interesting risks is how the price perceived by a technology is affected by the installed capacity of that same technology. To study this in more detail, the following table shows the prices captured by each technology in scenarios in which the installed capacity of the technology is modified, leaving the other technology with its base capacity, i.e., the most likely for 2025. For example, to study how the remuneration of solar photovoltaic energy is affected by the greater or lesser deployment of the same technology, only the installed capacity of solar energy will be varied respect to the base case.

Scenario	Solar PV price captured	Wind price captured	Difference
Base	38,4	74,7	36,3
Wind -3	-	82,2	14,9
Wind +3	-	67,3	
Solar +3	33,1	-	11,3
Solar-3	44,4	-	

Table 9: Prices captured by technologies in different scenarios

It should be noted that the first row of the difference column compares the price captured by the solar and wind technologies in the base scenario, while the other rows compare the prices obtained by the same technology in two different scenarios.

Specifically, analyzing solar photovoltaic energy, as explained at the beginning of this thesis, it has almost non-existent variable costs and, due to the existing type of electricity market, its market offers are very close to zero or even negative. This is good news for the consumer, who will be able to acquire cheaper energy at certain times thanks to this, but there is a problem, the sun, in a given electrical system such as, for example, the Spanish one, will give energy to these solar panels all at the same time (approximately). In other words, all the photovoltaic plants in Spain will start and finish generating energy at approximately the same time. This means that the presence of solar energy in the energy mix is highly concentrated in a certain period of time, which means that during these hours, the energy will normally be cheaper than during the rest of the day. Moreover, the more photovoltaic capacity is installed, the cheaper the energy will be in the middle hours on average and, therefore, the lower the remuneration this type of technology will receive. Summarizing, the biggest enemy of solar technology when it comes to making a profit is solar energy itself.

7.3.4 Economic Viability

The economic viability matrices are shown below:

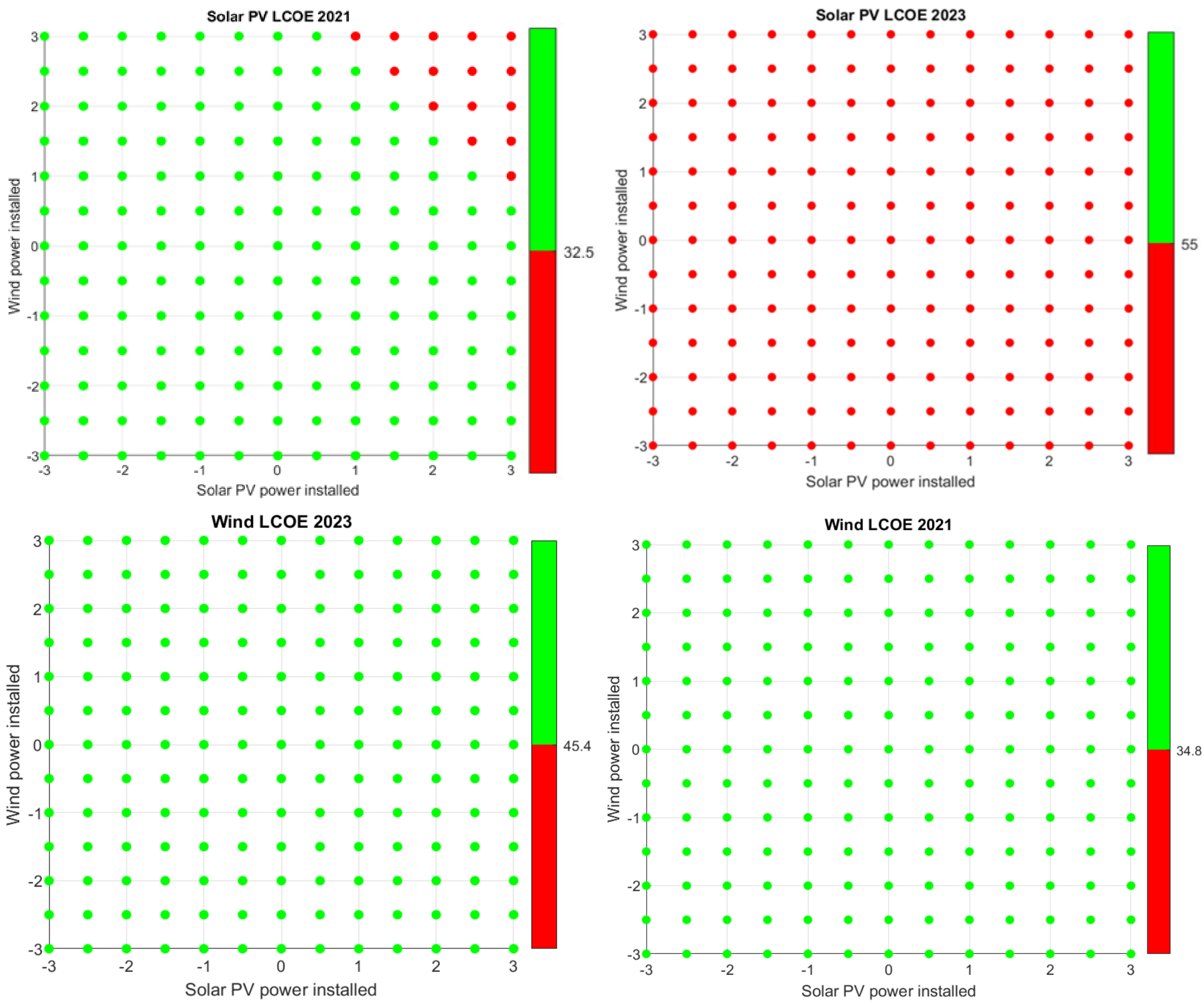


Figure 44: Economic viability matrices for the base case. Source: Own elaboration

By analyzing these four graphs, two clear conclusions can be drawn:

- Wind turbine investors, under normal conditions, should be able to make a return on their investment without any problem, since in all possible scenarios the price they capture is higher than both LCOEs.
- Investors in solar PV technology, due to the low capture ratio of this technology, do not achieve a return on investment in any scenario taking into account the average LCOE of 2023. However, as mentioned above, this LCOE is exceptionally high, so studying economic viability with the 2021 LCOE can be very useful in assessing the situation. Looking at this graph, we can see how the installation would pay for itself in many scenarios, although as more renewable capacity is installed, we can see how scenarios appear in which the capture price is no higher than the LCOE.

Given this situation, it can be concluded that, under these base case conditions, solar energy investors run a great risk of seeing their plant not pay off precisely because of overinvestment in renewable energies. In any case, if in the coming years the LCOE of this technology recovers its historical downward trend, there could be many scenarios in which this technology could continue to be profitable. In addition, investors in this type of technology, considering the remuneration they can obtain, could try to sign bilateral agreements to ensure the return on investment and not depend on market behavior. As for wind power technology, we can clearly see that it is a safer investment due to the capture ratios it presents in all scenarios. The problem with this type of technology is both the limited sites available for wind turbines and the operation, which is much more complicated than that of a photovoltaic plant.

7.4 Analysis of the remaining cases

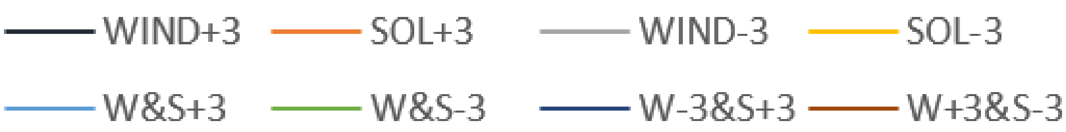
Once the base case has been studied in detail, we will proceed to analyze the other cases in which the price of gas will vary as indicated above. The relevant results, together with the sensitivity matrices, will be plotted together to analyze the cases as a whole.

First, the average monthly prices in 2025 for each case will be plotted with the most interesting scenarios as in the base case. The nomenclature to refer to the different cases will be as follows:

Gas price [Δ €/MWh] TTF and MIBGAS			
Base	+1 = G+1	+5 = G+5	Double = Gx2

Table 10: Nomenclature for the different cases

The color criteria for each scenario in every case are as follows:



Ilustration 2: Color criteria for each scenario in every case

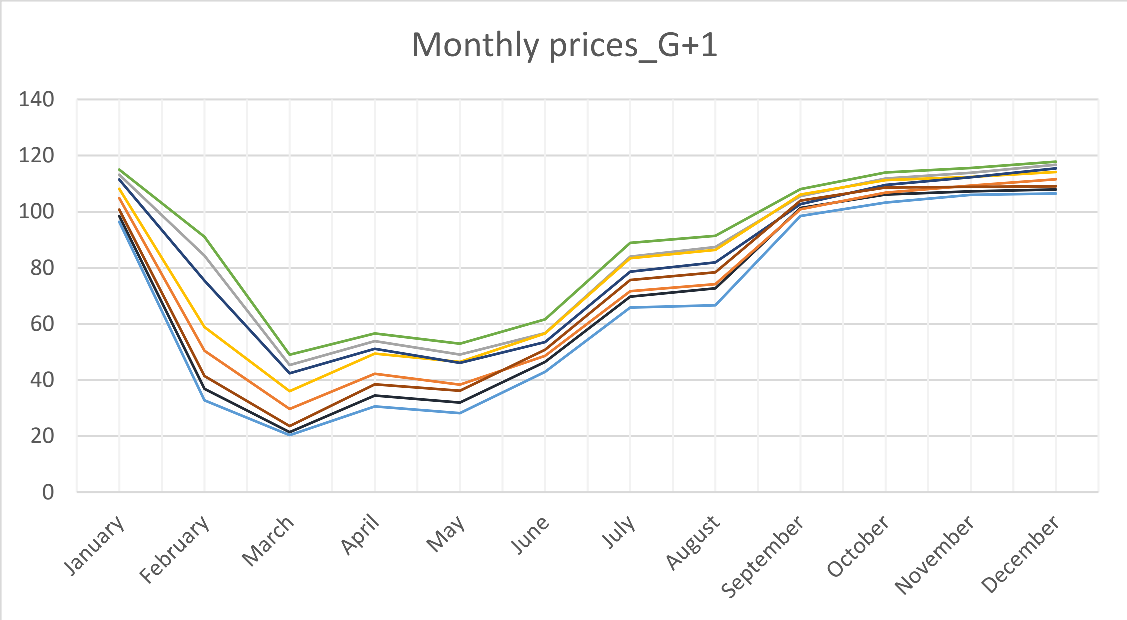


Figure 45: Monthly average day-ahead market prices in 2025 for the case G+1. Source: Own elaboration

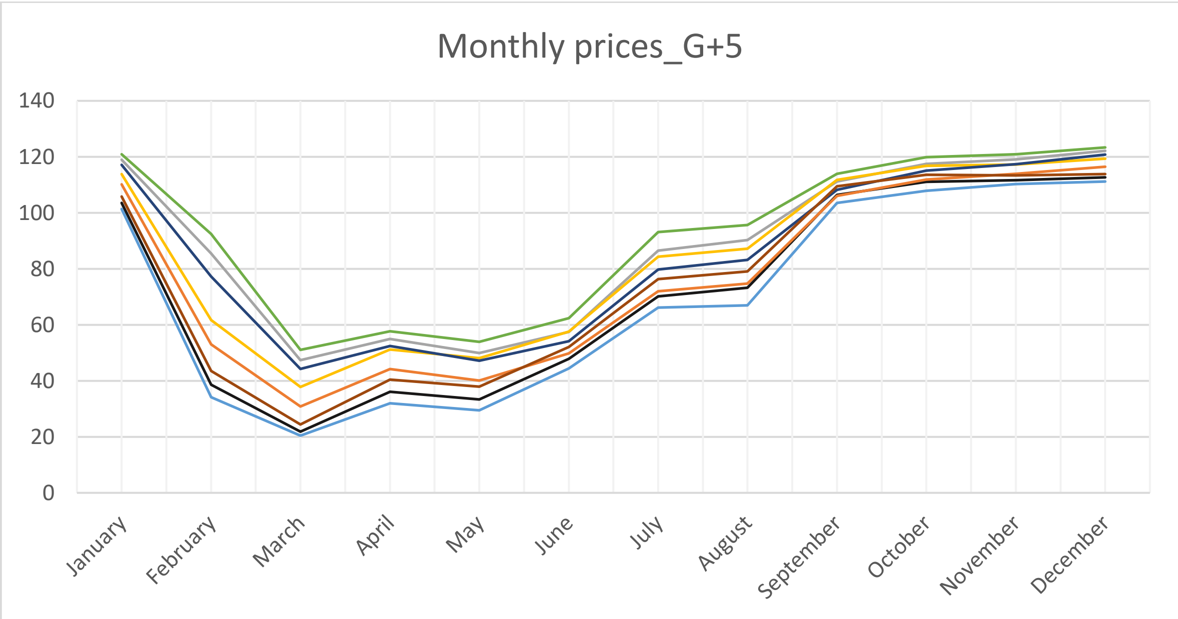


Figure 46: Monthly average day-ahead market prices in 2025 for the case G+5. Source: Own elaboration

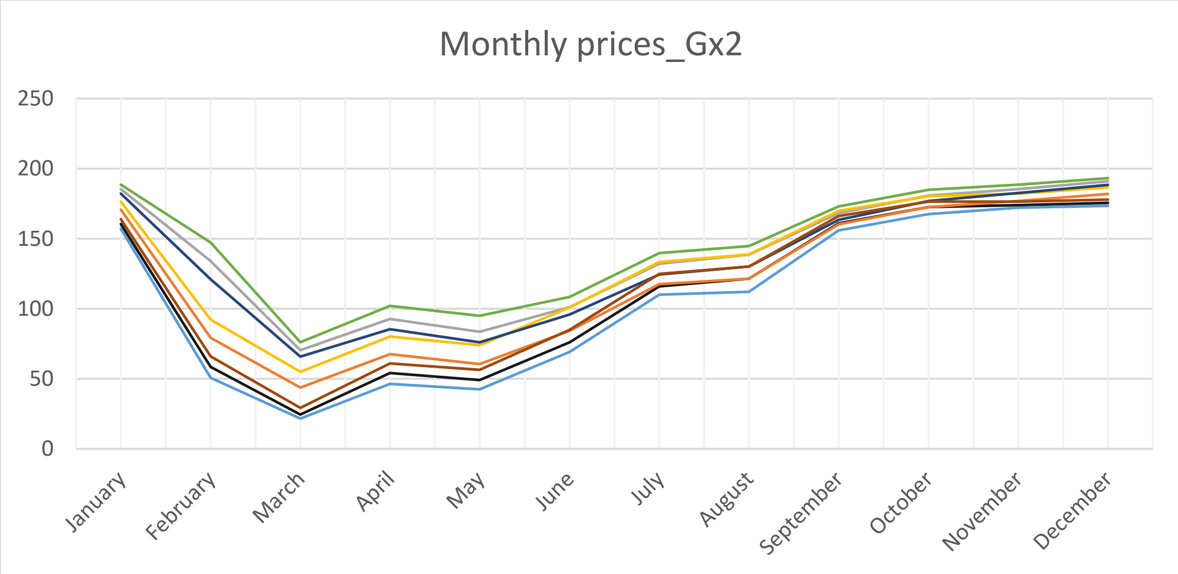


Figure 47: Monthly average day-ahead market prices in 2025 for the case Gx2. Source: Own elaboration

When examining these graphs, it becomes apparent that the rise in gas prices corresponds to a general upsurge in monthly costs, particularly during months when the presence of Combined Cycle Gas Turbines (CCGTs) in the energy mix is more prominent as in October and November where the price difference between the different scenarios is much smaller. Additionally, the substantial impact of wind technology on reducing average monthly prices is evident once again. Comparing two representative scenarios to demonstrate this, the installation of an additional 3GW of wind power (WIND+3) versus an equivalent increase in solar power (SOL+3), in all cases (different gas prices) we can clearly observe that, with the exception of August and September where they almost coincide, the price is systematically lower in the scenario where more wind power is installed instead of solar.

Next, the same analysis has been done as for the base case, comparing the maximum and minimum prices of the most relevant scenarios for each case. With this, we can calculate the maximum price difference during the year for the different scenarios and the difference between scenarios to check how the increase in installed renewable capacity affects these parameters.

G+1	Wind: +3 & Solar: +3	Wind: -3 & Solar: -3	Difference
Maximum price	106,5	117,8	11,3
Minimum price	20,3	49	28,7
Spread	86,2	68,8	17,4

Table 11: G+1 case

G+5	Wind: +3 & Solar: +3	Wind: -3 & Solar: -3	Difference
Maximum price	111,2	123,4	12,2
Minimum price	20,4	51,1	30,7
Spread	90,8	72,3	18,5

Table 12: G+5 Case

Gx2	Wind: +3 & Solar: +3	Wind: -3 & Solar: -3	Difference
Maximum price	173,5	193,2	19,7
Minimum price	21,6	76,1	54,5
Spread	151,9	117,1	34,8

Table 13: Gx2 case

The conclusions that can be drawn from the analysis of the results are as follows:

- The minimum price achieved throughout the year exhibits minimal dependence on the gas price when a substantial amount of renewable capacity is installed. This observation is derived from the systematic absence of significant variation in the minimum price in all cases in the scenario with the maximum expected renewable capacity (Wind: +3 & Solar: +3).

- The higher the gas price, the greater the difference between the spreads of the maximum and minimum price of each scenario. This reveals that the higher the gas price, the greater the impact of the amount of renewable power in the system on the annual price spread.

- The increase in gas prices increases the spread between the maximum and minimum price in both scenarios. It is worth noting the increase in the spread in the cases where more renewable is installed, as the minimum price remains almost constant in all three cases while the maximum price skyrockets with the increase in gas price, causing this maximum spread to reach almost 152 €/MWh, which could be a very interesting price signal for investors in storage technologies. This statement affects medium and long-term storage technologies like hydropower, although very likely the daily spread will also be affected by this phenomenon.

- The influence of renewables in reducing the price is directly proportional to the price of gas, since the difference between maximum and minimum prices between scenarios increases with the price of gas, being especially noticeable in the difference between minimum annual prices.

7.4.1 Sensitivity Analysis

As in the base case, the sensitivity matrices will be represented with the annual average prices of the day-ahead market price obtained from simulating all the scenarios mentioned in the methodology. The points will also be represented in three dimensions, thus being able to check whether, despite the variations in the gas price, a perfect plane is still obtained by joining all these points.

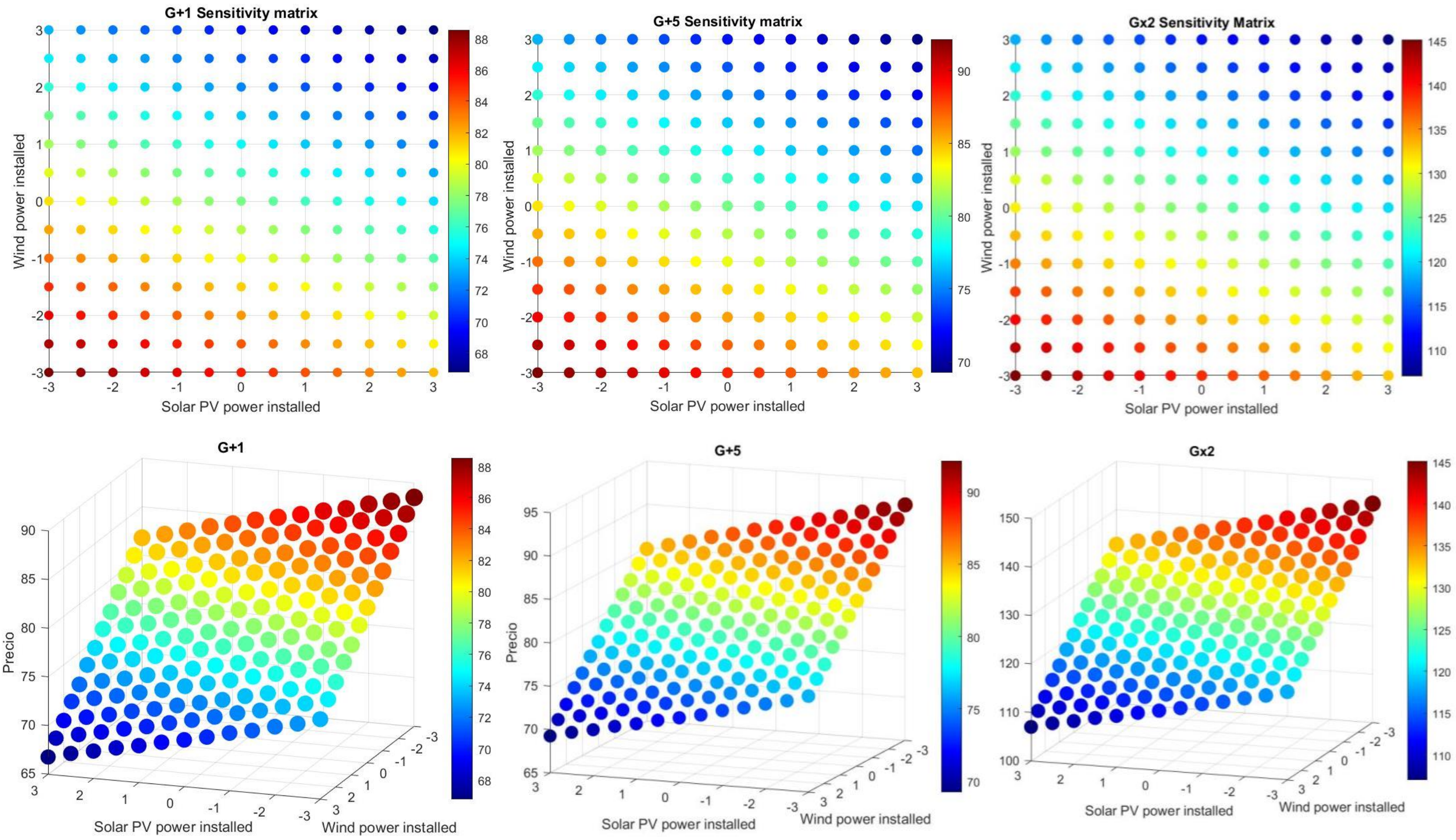


Figure 48: Sensitivity matrices for the cases G+1, G+5 and Gx2. 2D and 3D. Source: Own elaboration

Looking at the matrices, the first thing that can be observed is that they are practically identical, although the values obtained for each scenario, as expected, differ quite a lot. This is due to the fact that the color scale chosen to represent the average annual prices obtained is adapted to the values (market price), always assigning the maximum value to dark red and the minimum to dark blue. Having made this clarification, the conclusions obtained from analyzing these sensitivity matrices will be presented below:

- First, the maximum price occurs in the situation where less renewable capacity is installed and the gas price doubles with respect to the base case, reaching 145 EUR/MWh. On the contrary, the situation where the minimum price occurs is the situation where more renewables are installed and the gas price behaves as expected, reaching approximately 66 EUR/MWh. Thus, the tremendous influence that the three variables selected for the sensitivity study have on the average annual price of the day-ahead market can be seen, with a difference of 79 EUR/MWh between the maximum and minimum prices obtained.

- As in the base case analyzed, the increase in wind generation capacity reduces the average annual price to a greater extent than the increase in solar. This is true in all cases, confirming that, regardless of the price of gas, when it comes to reducing the average annual price, the increase in installed capacity of wind technology is more effective than solar. The following table shows the prices obtained for the scenarios where the installed capacity of one technology is increased and decreased up to ±3 GW while maintaining the installed capacity of the base case in the other.

	Wind: +3	Solar: +3	Wind: -3	Solar: -3
G+1	69,81	74,22	85,19	80,96
G+5	72,46	77,12	88,48	84,08
Gx2	112,33	120,05	138,7	131,15

Table 14: Average anual prices of different scenarios

- Observing the table above, not only confirms that by increasing the installed wind power capacity with respect to the base case, the average price decreases to a greater extent than in the scenario where this increase occurs in the installed solar capacity, but also that the decrease in installed wind power capacity increases the price to a greater extent than the decrease in installed solar capacity, which reveals the importance of wind energy in lowering the average annual market prices.

- As in the base case, by observing the figures in three dimensions, it can be seen that by joining the points obtained, a perfect plane is constructed. This indicates that, regardless of the gas price, the increase or decrease in the average market price that occurs when increasing or decreasing the installed capacity of one technology is independent of the installed capacity of the other technology. This makes it possible to derive scenario prices by performing fewer simulations than necessary. To explain this phenomenon, the price in the G+5 case will be derived for the scenario (+3,+3), which is 69,25 EUR/MWh, from the decreases in price with respect to the base case obtained for the scenario (+3,0) y (0,+3). It will be enough to measure the decreases of each scenario with respect to the base case and add them up, obtaining a final decrease that will have to be added (subtracted in this case) to the average price obtained for the base case.

	Base	Wind +3	Solar +3	Solar +3 & Wind +3
Price	80,49	72,46	77,12	
Increase		-8,03	-3,37	-11,4
Deducted price				69,09

It can be seen that the price obtained through this deduction is practically the same as that obtained in the simulation, with a small difference of: $69{,}25 - 69{,}09 = 0{,}16\,\frac{EUR}{MWh}$.

7.4.2 Capture Ratios Analysis

Once the conclusions of the sensitivity matrices have been obtained, we will proceed to represent both the capture ratios obtained for each case and the prices perceived by each technology.

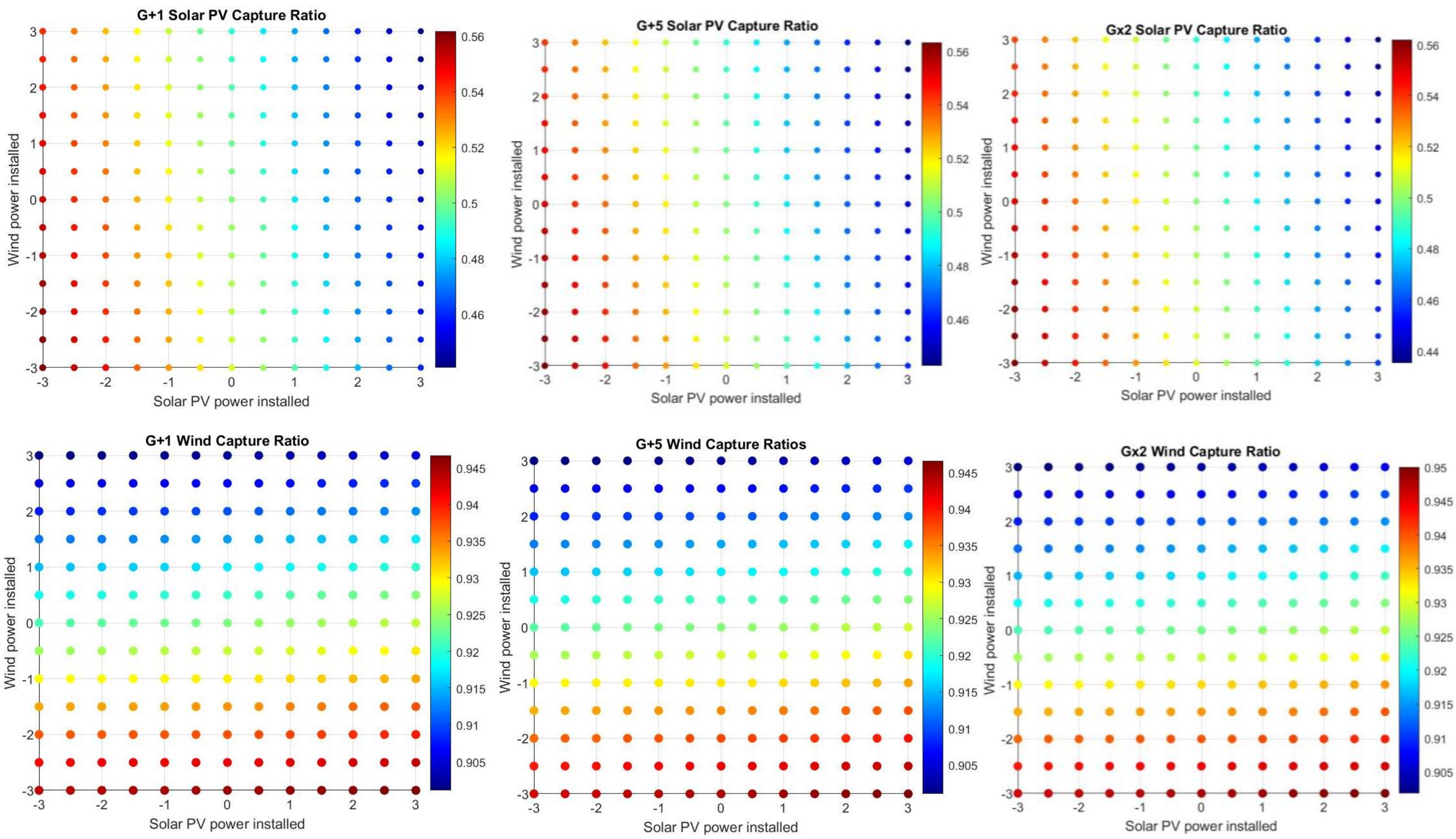


Figure 49: Capture ratios for Solar PV and Wind power for cases G+1, G+5 and Gx2. Source: Own elaboration

As with the sensitivity matrices, the capture ratio matrices are identical in the three cases, although unlike those previously analyzed, in this case it is not due to the color assignment of the maximum and minimum value, but rather the values are practically the same in the four cases, taking into account the base case. For this reason, the analysis carried out for the matrix in the base case is equally applicable to these three cases, adding that the percentage of the market price received by both solar and wind energy does not depend at all on the price of gas.

Once this analysis has been carried out, the matrices will be represented showing the market prices perceived by each technology in each case, which, as can be deduced, will vary depending on the established gas price.

7.4.3 Capture Prices Analysis

Below are the matrices with the prices captured by each renewable technology for each case.

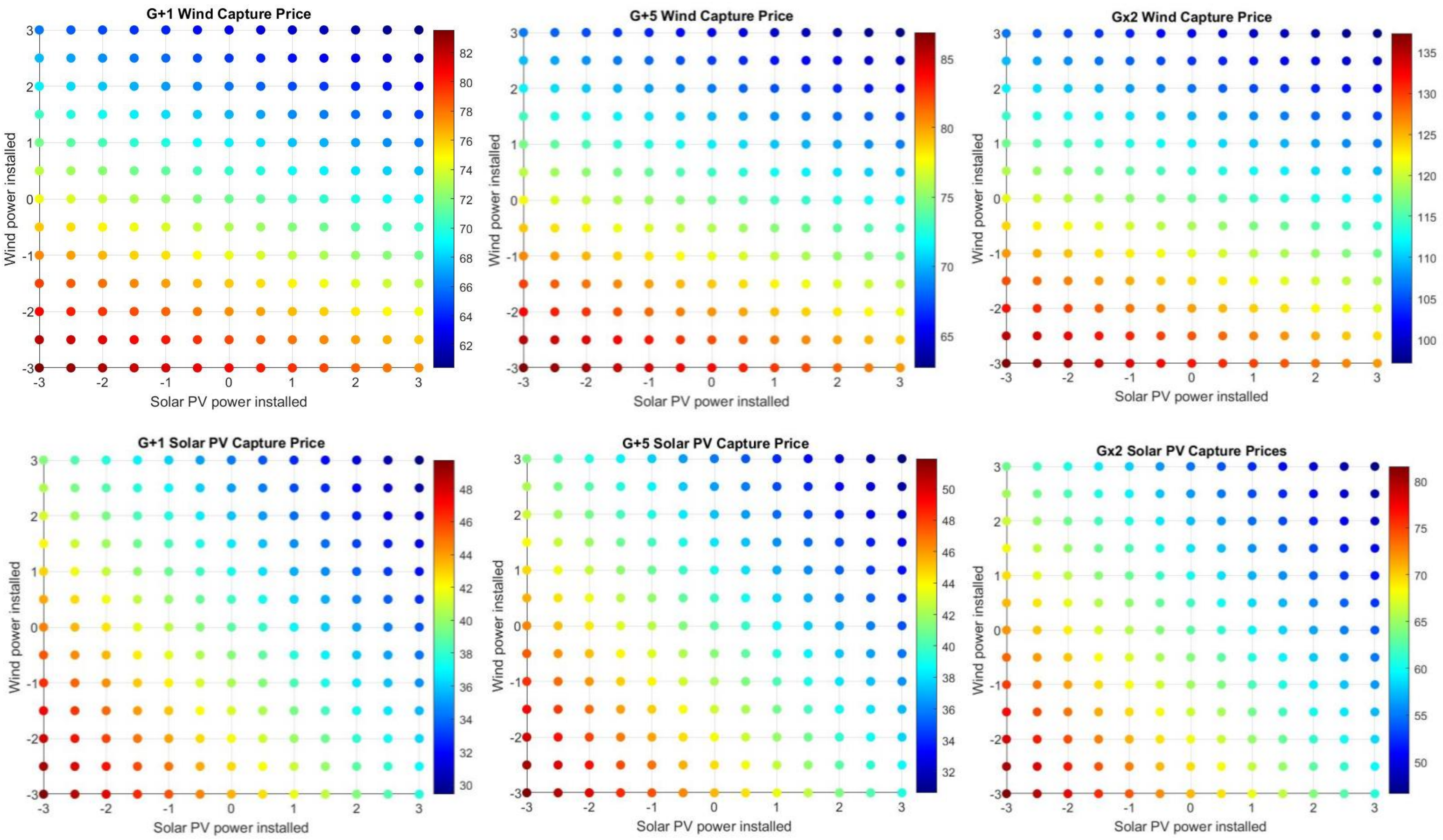


Figure 50: Capture prices for Solar PV and Wind power for cases G+1, G+5 and Gx2. Source: Own elaboration

As with the ratios and average annual market prices, the colors of the matrices are identical, indicating in this context that regardless of the gas price, the scenario where the technologies receive the highest remuneration is the scenario where the least renewables are installed and the scenario where they receive the lowest remuneration is the scenario where the highest possible renewable capacity is installed.

Despite this, the increase in captured price that occurs between one scenario and another is directly proportional to the price of gas, and this can be verified by observing the maximum and minimum prices indicated in the respective colored bars. The following tables show the maximum and minimum prices for each case and technology. The spread between the maximum and minimum annual price of each technology and the difference between the maximum and minimum between technologies are also shown.

G+1	Wind Capt Price	Solar Capt Price	Difference
Maximum price	83,5	49,7	33,8
Minimum price	60,4	29,4	31
Spread	23,1	20,3	

Table 15: G+1 case

G+5	Wind Capt Price	Solar Capt Price	Difference
Maximum price	86,9	51,9	35
Minimum price	62,7	30,6	32,1
Spread	24,2	21,3	

Table 16: G+5 case

Gx2	Wind Capt Price	Solar Capt Price	Difference
Maximum price	137,3	81,6	55,7
Minimum price	97,1	46,6	50,5
Spread	40,2	35	

Table 17: Gx2 case

Firstly, it is confirmed that, regardless of the price of gas, the price received by wind technology is higher than that received by solar in all scenarios. In fact, comparing in each case the minimum price perceived by wind with the maximum price perceived by solar, it can be seen how the price perceived by wind in the worst scenario (maximum installed renewable capacity) is higher than the price perceived by solar in the best scenario (minimum installed renewable capacity).

Another aspect to highlight is that the difference between maximum and minimum between technologies increases with the price of gas, meaning that the difference between the remuneration obtained by these technologies will be greater the higher the price of gas. This will be of vital importance when checking whether investors in this type of technology will be able to amortize their investments. This will be discussed in more detail in the next section.

Finally, it can be seen how the spread between the maximum and minimum prices received by each technology increases with the increase in the price of gas, showing that the influence of the installed capacity of renewable technologies in determining their remuneration increases with the price of gas. In addition, the spread obtained between the maximum and minimum price of the same technology is greater for wind technology in all three cases, indicating the importance of the factors studied in determining the price captured by wind technology.

7.4.4 Economic viability

In this section, as for the base case, the prices captured by each technology will be compared with their LCOE respectively. In this way, it will be possible to check whether the remuneration obtained for each MWh generated by each of these technologies in 2025 is higher than their total costs in that year.

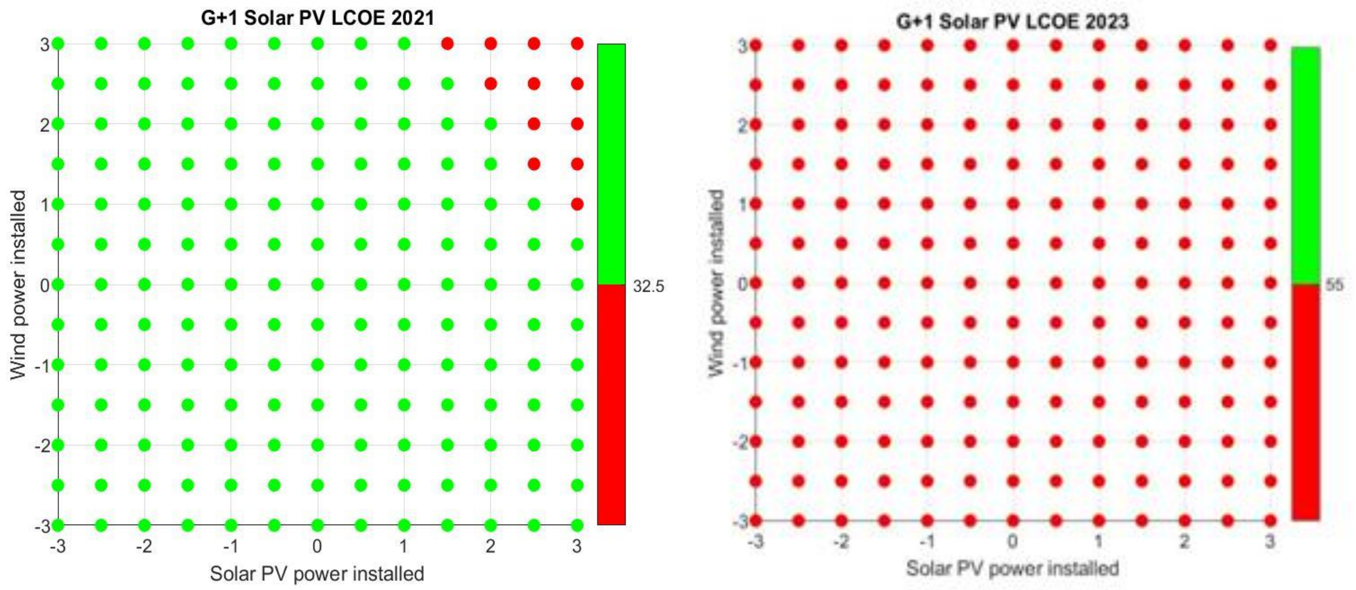


Figure 51: Solar PV economic viability matrices for the G+1 case. Source: Own elaboration

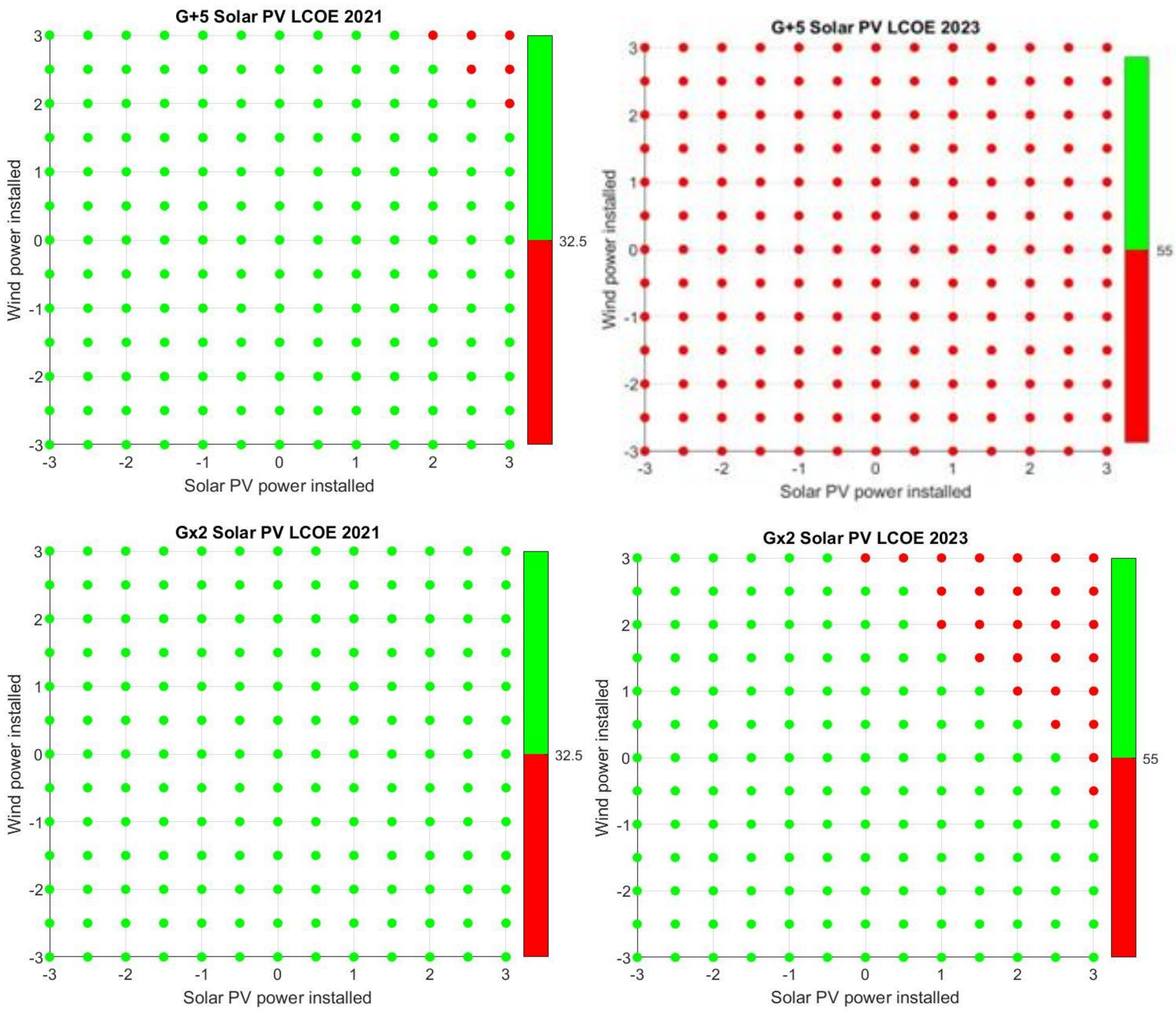


Figure 52: Solar PV economic viability matrices for the G+5 and Gx2 cases. Source: Own elaboration

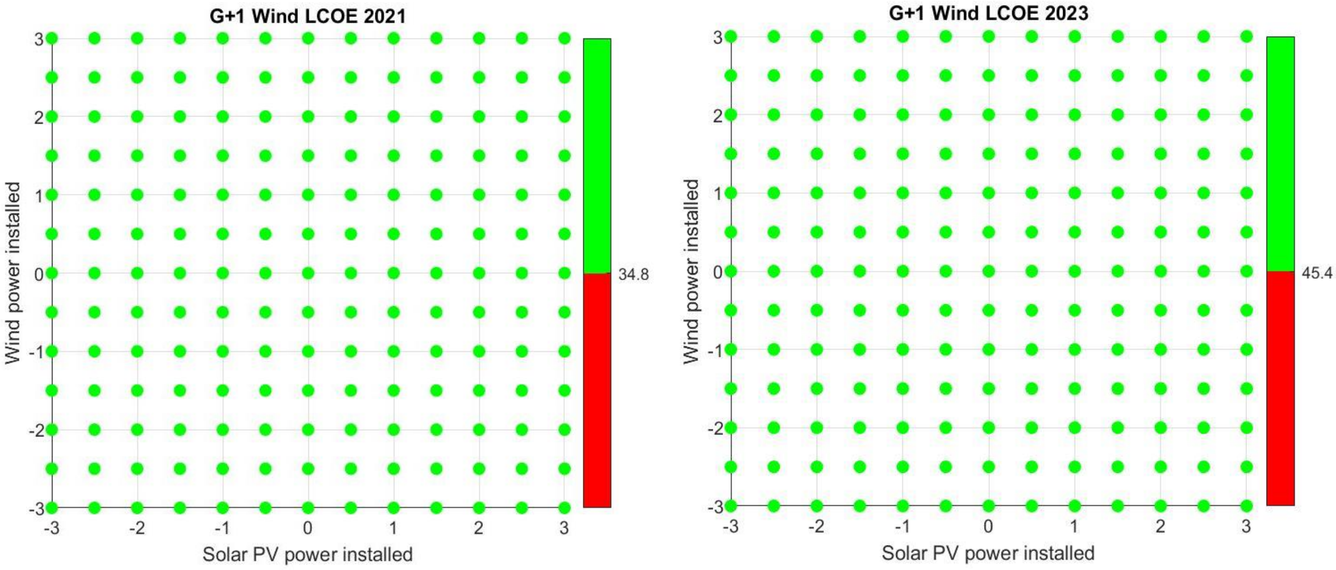


Figure 53: Wind power economic viability matrices for the G+1 case. Source: Own elaboration

As in the base case, the price captured by wind energy in the G+1 case is higher in all scenarios than its LCOE, both comparing the remuneration with the estimated LCOE in 2021 and in 2023. For this reason, it was decided not to represent the other cases for this technology, as it can be intuited that the economic viability condition will also be met. This indicates the potential remuneration that wind power could receive, since in all the cases and scenarios analyzed, the remuneration obtained by this technology is greater than its LCOE.

With respect to solar photovoltaic technology, it can be seen that the number of scenarios where the economic viability condition is met increases with the price of gas. It is worth highlighting the case where the price of gas doubles, since only in this case are there scenarios where the price received is greater than the LCOE of 2023. Moreover, it is in this case where in all scenarios the LCOE of 2021 is exceeded. This shows us how the increase in the price of fuels, specifically gas, is a positive indicator for renewable energies, since they will receive higher remuneration and investors will be able to amortize their installations, sending a price signal to new potential investors. In this way, there could be a strong boost in the installed capacity of renewable technologies, which paradoxically could pose problems for investors in solar technology in particular, since wind, despite receiving a lower remuneration as we saw in the interior section, continues to receive enough, due to its capture ratio, to be able to make the installation profitable in all scenarios.

Finally, the most relevant conclusions of the study will be presented.

8. Conclusions

During the last two years, the significant relevance of achieving energy independence on the European continent has become evident. The sudden and sharp increase in the price of electricity and the effects of climate change have highlighted the need to reduce dependence on fossil fuels for electricity generation. Consequently, the penetration and integration of renewable technologies has become an urgent and necessary priority to ensure greater stability and lower prices in the region's energy supply.

This objective is being pursued as soon as possible, as reflected by the increase in investments in this type of technology in recent years. Furthermore, analyzing the operation of these technologies and their situation in Spain, thanks to their complementarity, both seasonal and hourly, it could be possible that they could cover the entire electricity demand, although due to their intermittency, back-up technologies such as combined cycle plants will be necessary. To completely eliminate conventional technologies that use fossil fuels to generate electricity, it will be necessary to promote investment in and penetration of storage technologies that can vary their generation rapidly, such as solar thermal power plants, pumped hydroelectric plants or batteries.

The study carried out focused on analyzing the sensitivity of the market price to variations in solar PV and wind power installed capacity, as well as changes in gas prices. By constructing multiple sensitivity matrices and observing the behavior of the annual and monthly average market prices under different scenarios, valuable insights were gained regarding the interaction between renewable energy deployment and market dynamics. After a thorough analysis of the simulation results, a clear and convincing conclusion is reached: The greater integration of renewable technologies in the Spanish energy mix leads to a significant reduction in average prices, both monthly and annual, in the day-ahead market. A detailed examination of this phenomenon allows us to draw the following conclusions.

On one hand, by observing the relationship between the average monthly prices projected for the year 2025 and the level of renewable power integrated into the Spanish electricity system, without modifying the price of gas with respect to the base case, a noticeable trend emerges. As the installed renewable capacity increases, the average price decreases, but the spread between the maximum and minimum price increases. This shows that price stability is significantly affected by the integration of renewables into the system. A priori, this could be understood as something negative, however, given the current context where the entry of storage technologies could be differential, this type of price signals could be of great interest for investors in this type of technology. To gain deeper insights into this phenomenon, further simulations could be conducted, focusing on the hourly behavior of the day-ahead market.

Regarding the impact of individual technologies (solar pv and wind) on the market price, it was found that, in all the scenarios studied, the amount of installed wind power capacity has a greater effect on average market prices, both in terms of lowering them as more capacity is installed and in terms of making them more expensive when it is assumed that by 2025 there will be less installed capacity of this technology. This underscores the significant role of wind power in shaping market dynamics and price fluctuations.

As for how this penetration of renewable technologies would affect the remuneration of these technologies, it is concluded that:

- The percentage of market price that the solar PV producer would receive will be affected to a greater extent by the integration of renewable energies into the electricity system than wind energy.
- The capture ratio of solar technology is much lower than wind in all scenarios, so the average annual wind revenue per MWh generated, in all scenarios, will be higher than that of solar.
- It is clearly observed that the greater integration of renewables leads to lower remuneration for them. The worst scenario for renewable technologies when it comes to their remuneration is the scenario in which more renewable capacity is installed in the system, while the best scenario is the one in which the minimum renewable capacity is installed. Interestingly, both solar PV and wind technology remuneration are particularly penalized when their respective installed capacities increase.

Comparing the remuneration that investors in these technologies will obtain with the costs of each one, it can be concluded that wind turbine investors, under normal conditions, should be able to make a return on their investment without any problem, since in all possible scenarios the price they capture is higher than both LCOEs (2021 and 2023). However, investors in solar technology are in a more complicated situation, since, assuming that gas prices will be those proposed for the base case, comparing their remuneration with the LCOE of 2021, they would only amortize their installations in scenarios where the presence of renewables in the system is not too large, while comparing it with the LCOE assumed for 2023, they would not be able to amortize the installation in any scenario.

By modifying the gas price and analyzing the combined effect of the three variables studied, it is observed that these three variables have a tremendous influence on the average annual day-ahead market price, with a difference of 79 EUR/MWh between the maximum price obtained when it is assumed that the gas price doubles with respect to the base case and the installed renewable power is 3 GW less than the base case, and the minimum price obtained when the gas price is maintained at the value of the base case and the installed renewable power is increased by 3 GW with respect to the base case. In addition, the following relevant conclusions can be drawn:

- The minimum price achieved throughout the year shows a minimal dependence on the gas price when a substantial amount of renewable capacity is installed. However, when the installed renewable power decreases, the minimum price depends directly on the gas, increasing greatly the more expensive the fuel. This phenomenon highlights the importance of these technologies in maintaining minimum prices.
- As was deduced from the case where the gas price did not vary respect the base case, the greater presence of renewables increases the spread between the annual maximum

and minimum. This phenomenon is more pronounced when the gas price is higher, since the minimum price is maintained but the maximum price increases greatly. This increasing difference between the minimum and maximum monthly average price during the year as the installed renewable generation capacity increases could be a price signal for medium or long-term storage technologies such as hydroelectric plants with a reservoir, and not only that, since fuels such as gas, which can be stored, could take advantage of this greater difference.

Analyzing the prices captured by each technology as gas prices change it is confirmed that, regardless of the price of gas, the price received by wind technology is higher than that received by solar in all scenarios. In fact, comparing in each case (same gas price for the different scenarios) the minimum price perceived by wind with the maximum price perceived by solar, it can be seen how the price perceived by wind in the worst scenario (maximum installed renewable capacity) is higher than the price perceived by solar in the best scenario (minimum installed renewable capacity). Also, the difference between the remuneration obtained by these technologies will be greater the higher the price of gas. This will be of vital importance when checking whether investors in this type of technology will be able to amortize their investments.

Comparing these remunerations with the costs associated with each technology, it can be seen once again that investors in wind power technology could amortize their installations regardless of the price of gas or the installed renewable capacity. With respect to solar photovoltaic technology, it is observed that the number of scenarios in which the economic viability condition is met increases with the price of gas. It should be noted that investors in this technology, in the case of having the associated costs estimated for 2023, would only be able to amortize their installation if the price of gas were to rise sharply, as observed in the case where the price of this fossil fuel is multiplied by two with respect to the base case, simulating a geopolitical event such as the war in Ukraine. Moreover, it is in this case where in all scenarios the 2021 LCOE is exceeded. This shows us how the increase in the price of fuels, specifically gas, can be a positive indicator for renewable energies, as they will receive higher remuneration and investors will be able to amortize their installations, sending a price signal to new potential investors.

Finally, from the three-dimensional representations of the sensitivity matrices, it can be concluded that the increase or decrease produced in the day-ahead market price by a change in the installed capacity of any of the renewable technologies analyzed is independent of the other technology. This conclusion would allow a study similar to the one conducted but adding a greater number of cases and scenarios to be developed, since the number of simulations to be carried out to achieve the desired results would be much lower.

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ANNEX I

In this annex, all the results of the annual average prices of the day-ahead market in 2025 obtained by simulating each case and scenario will be represented. The annual capture ratios for each technology have also been represented according to the established gas price and the installed solar and wind capacities. When defining the values of these parameters, the increase with respect to the values of the base case and scenario will be represented, that is, with respect to the values in Table 4.

Gas (Δ€/MWh)	Solar PV (ΔGW)	Wind (ΔGW)	Price (€/MWh)	Wind Capture Ratio	Solar PV Capture Ratio
0	0	0	76,67	0,92359	0,50115
0	0	0,5	75,51	0,92042	0,49988
0	0	1	74,19	0,9171	0,49853
0	0	1,5	73	0,91377	0,49657
0	0	2	71,65	0,91034	0,49469
0	0	2,5	70,51	0,90672	0,49296
0	0	3	69,13	0,90218	0,49123
0	0	-0,5	78,02	0,92688	0,50329
0	0	-1	79,15	0,93005	0,50475
0	0	-1,5	80,5	0,9342	0,50656
0	0	-2	81,64	0,93732	0,50809
0	0	-2,5	83,06	0,94174	0,50942
0	0	-3	84,3	0,94547	0,51122
0	-3	-3	87,61	0,94406	0,56119
0	-3	-2,5	86,58	0,94115	0,55965
0	-3	-2	85,18	0,93712	0,55833
0	-3	-1,5	83,94	0,9335	0,55678
0	-3	-1	82,56	0,92963	0,55397
0	-3	-0,5	81,4	0,92508	0,55284
0	-3	3	72,49	0,90102	0,54057
0	-3	2,5	73,9	0,90508	0,54212
0	-3	2	75,03	0,90758	0,54369
0	-3	1,5	76,47	0,91173	0,54589
0	-3	1	77,59	0,9149	0,54729
0	-3	0,5	78,93	0,91846	0,54878
0	-3	0	80,09	0,92153	0,55116
0	-2	-3	86,51	0,94435	0,54543
0	-2	-2,5	85,44	0,9414	0,54318
0	-2	-2	83,92	0,93706	0,5408
0	-2	-1,5	82,73	0,93357	0,53923
0	-2	-1	81,42	0,92959	0,53742
0	-2	-0,5	80,22	0,92543	0,53596
0	-2	3	71,31	0,90126	0,52359
0	-2	2,5	72,73	0,90592	0,52563

0	-2	2	73,87	0,90863	0,52741
0	-2	1,5	75,23	0,91215	0,52837
0	-2	1	76,39	0,91567	0,53021
0	-2	0,5	77,78	0,91929	0,53231
0	-2	0	78,91	0,92217	0,53374
0	-1	-3	85,39	0,94488	0,52801
0	-1	-2,5	84,25	0,94166	0,5265
0	-1	-2	82,77	0,93722	0,52476
0	-1	-1,5	81,61	0,93383	0,52292
0	-1	-1	80,27	0,92989	0,52115
0	-1	-0,5	79,09	0,92617	0,51905
0	-1	3	70,26	0,90166	0,50908
0	-1	2,5	71,65	0,90642	0,51018
0	-1	2	72,74	0,90935	0,51149
0	-1	1,5	74,11	0,91279	0,51306
0	-1	1	75,27	0,91616	0,51452
0	-1	0,5	76,62	0,91994	0,51621
0	-1	0	77,79	0,92299	0,51741
0	3	-3	80,96	0,94678	0,45946
0	3	-2,5	79,77	0,94333	0,45852
0	3	-2	78,39	0,93964	0,45697
0	3	-1,5	77,29	0,9372	0,45561
0	3	-1	75,92	0,93352	0,4542
0	3	-0,5	74,77	0,93024	0,45249
0	3	3	66,11	0,90527	0,44021
0	3	2,5	67,41	0,90928	0,44271
0	3	2	68,57	0,91308	0,44479
0	3	1,5	69,9	0,91744	0,44675
0	3	1	70,99	0,92049	0,44794
0	3	0,5	72,36	0,92407	0,4495
0	3	0	73,46	0,927	0,45116
0	2	-3	82,09	0,94628	0,47717
0	2	-2,5	80,84	0,94267	0,47473
0	2	-2	79,4	0,93868	0,47225
0	2	-1,5	78,3	0,93607	0,47084
0	2	-1	76,94	0,93228	0,46926
0	2	-0,5	75,79	0,929	0,46819
0	2	3	67,13	0,90407	0,4592
0	2	2,5	68,46	0,90796	0,46108
0	2	2	69,6	0,91223	0,4622
0	2	1,5	70,9	0,91595	0,46346
0	2	1	72,02	0,91917	0,46447
0	2	0,5	73,37	0,92284	0,46556
0	2	0	74,45	0,92576	0,46681
0	1	-3	83,23	0,94571	0,495

0	1	-2,5	81,98	0,94199	0,49362
0	1	-2	80,57	0,93783	0,49182
0	1	-1,5	79,42	0,93483	0,48985
0	1	-1	78,08	0,93105	0,48779
0	1	-0,5	76,88	0,92774	0,48551
0	1	3	68,11	0,90312	0,47506
0	1	2,5	69,44	0,90728	0,47607
0	1	2	70,6	0,91156	0,47712
0	1	1,5	71,88	0,91492	0,47834
0	1	1	73,01	0,91809	0,47928
0	1	0,5	74,38	0,9216	0,48146
0	1	0	75,53	0,92467	0,48294
0	-2,5	-3	86,99	0,94436	0,55203
0	-2,5	-2,5	85,94	0,94141	0,55061
0	-2,5	-2	84,49	0,93724	0,54885
0	-2,5	-1,5	83,26	0,93344	0,54723
0	-2,5	-1	81,93	0,92967	0,54494
0	-2,5	-0,5	80,75	0,92522	0,54343
0	-2,5	3	71,83	0,9012	0,53123
0	-2,5	2,5	73,26	0,90564	0,53327
0	-2,5	2	74,38	0,90815	0,53457
0	-2,5	1,5	75,78	0,912	0,53619
0	-2,5	1	76,93	0,91529	0,53795
0	-2,5	0,5	78,32	0,91886	0,54016
0	-2,5	0	79,42	0,92185	0,54144
0	-1,5	-3	85,86	0,94472	0,53479
0	-1,5	-2,5	84,78	0,94165	0,53357
0	-1,5	-2	83,28	0,93725	0,53196
0	-1,5	-1,5	82,12	0,93381	0,53054
0	-1,5	-1	80,76	0,92964	0,52802
0	-1,5	-0,5	79,59	0,92586	0,52657
0	-1,5	3	70,73	0,90147	0,51577
0	-1,5	2,5	72,12	0,90625	0,51692
0	-1,5	2	73,24	0,90907	0,51874
0	-1,5	1,5	74,61	0,91255	0,51981
0	-1,5	1	75,77	0,91588	0,52147
0	-1,5	0,5	77,14	0,91966	0,52323
0	-1,5	0	78,3	0,92261	0,52484
0	-0,5	-3	84,82	0,94522	0,51923
0	-0,5	-2,5	83,59	0,94168	0,5172
0	-0,5	-2	82,12	0,93728	0,51524
0	-0,5	-1,5	80,98	0,93399	0,51348
0	-0,5	-1	79,65	0,93008	0,51208
0	-0,5	-0,5	78,5	0,92659	0,51055
0	-0,5	3	69,62	0,90188	0,49895

0	-0,5	2,5	71,04	0,90668	0,50143
0	-0,5	2	72,15	0,90983	0,50284
0	-0,5	1,5	73,51	0,91335	0,50448
0	-0,5	1	74,66	0,91658	0,50542
0	-0,5	0,5	76	0,92023	0,50709
0	-0,5	0	77,17	0,92334	0,50886
0	2,5	-3	81,53	0,94642	0,46796
0	2,5	-2,5	80,33	0,94291	0,46676
0	2,5	-2	78,95	0,93911	0,46547
0	2,5	-1,5	77,86	0,93644	0,46426
0	2,5	-1	76,49	0,93269	0,46288
0	2,5	-0,5	75,34	0,92939	0,46181
0	2,5	3	66,68	0,90462	0,45107
0	2,5	2,5	67,98	0,90852	0,45285
0	2,5	2	69,13	0,9126	0,45415
0	2,5	1,5	70,43	0,91659	0,45595
0	2,5	1	71,56	0,91972	0,45752
0	2,5	0,5	72,93	0,92339	0,45886
0	2,5	0	74	0,92616	0,46001
0	1,5	-3	82,73	0,94589	0,48739
0	1,5	-2,5	81,47	0,9423	0,48525
0	1,5	-2	80,07	0,93817	0,4838
0	1,5	-1,5	78,89	0,93532	0,4807
0	1,5	-1	77,52	0,93166	0,47803
0	1,5	-0,5	76,35	0,92842	0,47663
0	1,5	3	67,67	0,90363	0,46803
0	1,5	2,5	68,99	0,90757	0,46915
0	1,5	2	70,14	0,91196	0,47024
0	1,5	1,5	71,44	0,91538	0,47153
0	1,5	1	72,57	0,91864	0,47242
0	1,5	0,5	73,91	0,92229	0,4737
0	1,5	0	75,02	0,92524	0,47476
0	0,5	-3	83,82	0,94547	0,50399
0	0,5	-2,5	82,58	0,94175	0,50268
0	0,5	-2	81,16	0,93751	0,50094
0	0,5	-1,5	80,02	0,93439	0,49951
0	0,5	-1	78,69	0,9304	0,49785
0	0,5	-0,5	77,53	0,92711	0,49627
0	0,5	3	68,67	0,90254	0,48365
0	0,5	2,5	70,01	0,90664	0,48552
0	0,5	2	71,16	0,91076	0,48656
0	0,5	1,5	72,49	0,9142	0,48802
0	0,5	1	73,65	0,91757	0,48964
0	0,5	0,5	75,01	0,92093	0,49194
0	0,5	0	76,17	0,92406	0,49373

1	-3	-3	88,53	0,94376	0,56176
1	-3	-2,5	87,45	0,94084	0,56025
1	-3	-2	86,07	0,93688	0,55899
1	-3	-1,5	84,86	0,93331	0,55737
1	-3	-1	83,46	0,92957	0,55451
1	-3	-0,5	82,28	0,92513	0,55329
1	-3	3	73,23	0,90108	0,54096
1	-3	2,5	74,65	0,90511	0,5425
1	-3	2	75,8	0,90776	0,54401
1	-3	1,5	77,25	0,91189	0,54621
1	-3	1	78,38	0,91503	0,54763
1	-3	0,5	79,77	0,91853	0,54908
1	-3	0	80,96	0,92152	0,55155
1	-2,5	-3	87,91	0,9441	0,55273
1	-2,5	-2,5	86,84	0,94118	0,5514
1	-2,5	-2	85,39	0,93695	0,54954
1	-2,5	-1,5	84,17	0,93335	0,54782
1	-2,5	-1	82,81	0,92963	0,5454
1	-2,5	-0,5	81,62	0,92526	0,54387
1	-2,5	3	72,55	0,9013	0,53155
1	-2,5	2,5	74	0,90566	0,53357
1	-2,5	2	75,15	0,90831	0,53489
1	-2,5	1,5	76,55	0,91214	0,5365
1	-2,5	1	77,7	0,91541	0,5383
1	-2,5	0,5	79,13	0,91898	0,54048
1	-2,5	0	80,27	0,92186	0,54187
1	-2	-3	87,41	0,94416	0,54604
1	-2	-2,5	86,32	0,94119	0,54379
1	-2	-2	84,81	0,93688	0,5413
1	-2	-1,5	83,61	0,9335	0,53975
1	-2	-1	82,29	0,9297	0,53786
1	-2	-0,5	81,09	0,92547	0,53636
1	-2	3	72,03	0,90135	0,52392
1	-2	2,5	73,46	0,90593	0,52609
1	-2	2	74,63	0,90876	0,52781
1	-2	1,5	76	0,91229	0,52877
1	-2	1	77,17	0,91577	0,53069
1	-2	0,5	78,57	0,91939	0,53268
1	-2	0	79,74	0,9222	0,53412
1	-1,5	-3	86,72	0,94446	0,53523
1	-1,5	-2,5	85,67	0,9415	0,53397
1	-1,5	-2	84,17	0,93709	0,5325
1	-1,5	-1,5	83	0,93377	0,53092
1	-1,5	-1	81,62	0,9296	0,52838
1	-1,5	-0,5	80,44	0,92589	0,52699

1	-1,5	3	71,42	0,90147	0,51617
1	-1,5	2,5	72,85	0,90631	0,51724
1	-1,5	2	74	0,90919	0,51902
1	-1,5	1,5	75,38	0,91266	0,52019
1	-1,5	1	76,53	0,91595	0,52195
1	-1,5	0,5	77,93	0,91983	0,52365
1	-1,5	0	79,1	0,92273	0,52526
1	-1	-3	86,27	0,94461	0,52856
1	-1	-2,5	85,14	0,94145	0,52701
1	-1	-2	83,65	0,93706	0,5252
1	-1	-1,5	82,48	0,93379	0,52335
1	-1	-1	81,14	0,92989	0,52167
1	-1	-0,5	79,93	0,92618	0,51965
1	-1	3	70,95	0,90165	0,50951
1	-1	2,5	72,37	0,9065	0,51065
1	-1	2	73,49	0,90943	0,51203
1	-1	1,5	74,87	0,91289	0,51347
1	-1	1	76,03	0,91624	0,51488
1	-1	0,5	77,41	0,9201	0,51654
1	-1	0	78,58	0,92307	0,51784
1	-0,5	-3	85,69	0,9449	0,51967
1	-0,5	-2,5	84,47	0,94151	0,51763
1	-0,5	-2	83	0,93721	0,51571
1	-0,5	-1,5	81,84	0,93404	0,51386
1	-0,5	-1	80,5	0,93007	0,51248
1	-0,5	-0,5	79,31	0,92666	0,51101
1	-0,5	3	70,32	0,90191	0,49935
1	-0,5	2,5	71,77	0,90674	0,50193
1	-0,5	2	72,89	0,90986	0,50332
1	-0,5	1,5	74,28	0,91345	0,50495
1	-0,5	1	75,43	0,91665	0,50589
1	-0,5	0,5	76,78	0,92043	0,50756
1	-0,5	0	77,96	0,92345	0,50919
1	3	-3	81,8	0,94665	0,46011
1	3	-2,5	80,61	0,94334	0,45909
1	3	-2	79,21	0,93971	0,4576
1	3	-1,5	78,07	0,93732	0,45624
1	3	-1	76,69	0,93341	0,45478
1	3	-0,5	75,54	0,9304	0,45302
1	3	3	66,76	0,90531	0,44074
1	3	2,5	68,07	0,90928	0,44323
1	3	2	69,26	0,91312	0,4453
1	3	1,5	70,59	0,91745	0,44727
1	3	1	71,72	0,92057	0,44846
1	3	0,5	73,1	0,92415	0,45006

1	3	0	74,22	0,92705	0,4517
1	2,5	-3	82,38	0,94632	0,46858
1	2,5	-2,5	81,17	0,94291	0,46747
1	2,5	-2	79,79	0,93914	0,46627
1	2,5	-1,5	78,65	0,93655	0,46493
1	2,5	-1	77,28	0,93282	0,46351
1	2,5	-0,5	76,12	0,92955	0,46242
1	2,5	3	67,34	0,90462	0,4516
1	2,5	2,5	68,66	0,90853	0,45333
1	2,5	2	69,82	0,9126	0,45469
1	2,5	1,5	71,14	0,91662	0,45654
1	2,5	1	72,3	0,91973	0,45813
1	2,5	0,5	73,68	0,92346	0,45949
1	2,5	0	74,76	0,92621	0,4606
1	2	-3	82,93	0,94606	0,47779
1	2	-2,5	81,67	0,94263	0,4753
1	2	-2	80,24	0,93871	0,47278
1	2	-1,5	79,1	0,93622	0,47139
1	2	-1	77,72	0,93233	0,46983
1	2	-0,5	76,56	0,9291	0,4688
1	2	3	67,8	0,90406	0,45975
1	2	2,5	69,14	0,90796	0,46157
1	2	2	70,3	0,91224	0,46272
1	2	1,5	71,61	0,916	0,46401
1	2	1	72,76	0,91923	0,46508
1	2	0,5	74,12	0,92296	0,46604
1	2	0	75,23	0,92586	0,4673
1	1,5	-3	83,59	0,94567	0,48821
1	1,5	-2,5	82,32	0,94212	0,48608
1	1,5	-2	80,93	0,93814	0,48457
1	1,5	-1,5	79,72	0,93542	0,48127
1	1,5	-1	78,3	0,93162	0,47866
1	1,5	-0,5	77,13	0,92848	0,47727
1	1,5	3	68,34	0,90362	0,46853
1	1,5	2,5	69,67	0,90757	0,46963
1	1,5	2	70,86	0,91203	0,4708
1	1,5	1,5	72,16	0,91545	0,47215
1	1,5	1	73,32	0,9187	0,47313
1	1,5	0,5	74,66	0,92236	0,47435
1	1,5	0	75,79	0,92531	0,47543
1	1	-3	84,09	0,94547	0,49569
1	1	-2,5	82,83	0,94183	0,49415
1	1	-2	81,43	0,93781	0,49245
1	1	-1,5	80,27	0,93492	0,49045
1	1	-1	78,87	0,93107	0,48839

1	1	-0,5	77,66	0,92778	0,4861
1	1	3	68,79	0,90313	0,47561
1	1	2,5	70,13	0,90727	0,47654
1	1	2	71,31	0,91163	0,47773
1	1	1,5	72,63	0,91502	0,47882
1	1	1	73,77	0,91818	0,47979
1	1	0,5	75,14	0,92174	0,48207
1	1	0	76,3	0,92477	0,48357
1	0,5	-3	84,69	0,9452	0,50455
1	0,5	-2,5	83,44	0,94157	0,50317
1	0,5	-2	82,01	0,93746	0,5015
1	0,5	-1,5	80,89	0,93447	0,5001
1	0,5	-1	79,5	0,93041	0,49839
1	0,5	-0,5	78,31	0,92712	0,49686
1	0,5	3	69,35	0,90255	0,48404
1	0,5	2,5	70,71	0,9067	0,48591
1	0,5	2	71,89	0,91081	0,48709
1	0,5	1,5	73,24	0,91433	0,48856
1	0,5	1	74,42	0,9177	0,49014
1	0,5	0,5	75,77	0,92109	0,49244
1	0,5	0	76,94	0,92417	0,49424
1	0	-3	85,19	0,94525	0,51182
1	0	-2,5	83,93	0,94157	0,50985
1	0	-2	82,51	0,93729	0,50845
1	0	-1,5	81,37	0,93426	0,5069
1	0	-1	79,98	0,93007	0,50519
1	0	-0,5	78,81	0,92691	0,50387
1	0	3	69,81	0,90222	0,49162
1	0	2,5	71,22	0,9068	0,49333
1	0	2	72,37	0,9104	0,49518
1	0	1,5	73,75	0,91388	0,49693
1	0	1	74,96	0,91722	0,49891
1	0	0,5	76,28	0,9206	0,50032
1	0	0	77,45	0,92372	0,50162
5	-3	-3	92,15	0,94264	0,56328
5	-3	-2,5	91	0,93976	0,56163
5	-3	-2	89,55	0,93623	0,56024
5	-3	-1,5	88,22	0,93303	0,55876
5	-3	-1	86,71	0,92964	0,55574
5	-3	-0,5	85,44	0,92544	0,55443
5	-3	3	76,08	0,90104	0,54177
5	-3	2,5	77,56	0,90523	0,5435
5	-3	2	78,74	0,90795	0,54513
5	-3	1,5	80,25	0,91213	0,54715
5	-3	1	81,45	0,91536	0,54853

5	-3	0,5	82,86	0,91898	0,55003
5	-3	0	84,08	0,92201	0,55259
5	-2,5	-3	91,47	0,94291	0,55443
5	-2,5	-2,5	90,34	0,94005	0,55308
5	-2,5	-2	88,79	0,93646	0,55103
5	-2,5	-1,5	87,46	0,93331	0,54919
5	-2,5	-1	86,02	0,9298	0,54637
5	-2,5	-0,5	84,74	0,92565	0,5448
5	-2,5	3	75,36	0,90114	0,53279
5	-2,5	2,5	76,89	0,90573	0,53459
5	-2,5	2	78,07	0,90853	0,53592
5	-2,5	1,5	79,54	0,91246	0,53734
5	-2,5	1	80,77	0,91562	0,53928
5	-2,5	0,5	82,2	0,91935	0,54131
5	-2,5	0	83,37	0,92229	0,54284
5	-2	-3	90,96	0,94311	0,54759
5	-2	-2,5	89,78	0,94032	0,54521
5	-2	-2	88,15	0,93655	0,54265
5	-2	-1,5	86,85	0,93363	0,54087
5	-2	-1	85,44	0,92986	0,53896
5	-2	-0,5	84,21	0,92587	0,53741
5	-2	3	74,8	0,9012	0,52495
5	-2	2,5	76,32	0,90596	0,52695
5	-2	2	77,54	0,90896	0,52877
5	-2	1,5	78,97	0,91258	0,52966
5	-2	1	80,19	0,91596	0,5315
5	-2	0,5	81,65	0,91978	0,53353
5	-2	0	82,81	0,92262	0,5352
5	-1,5	-3	90,22	0,94356	0,53642
5	-1,5	-2,5	89,05	0,94077	0,53525
5	-1,5	-2	87,42	0,93698	0,53372
5	-1,5	-1,5	86,21	0,93398	0,53194
5	-1,5	-1	84,73	0,92994	0,52938
5	-1,5	-0,5	83,53	0,92638	0,52776
5	-1,5	3	74,17	0,90134	0,51737
5	-1,5	2,5	75,66	0,90619	0,51844
5	-1,5	2	76,9	0,9093	0,52029
5	-1,5	1,5	78,32	0,91297	0,52122
5	-1,5	1	79,53	0,91616	0,523
5	-1,5	0,5	80,99	0,92021	0,52467
5	-1,5	0	82,16	0,92313	0,52607
5	-1	-3	89,7	0,94374	0,52994
5	-1	-2,5	88,5	0,94098	0,52835
5	-1	-2	86,83	0,93712	0,52645
5	-1	-1,5	85,63	0,93401	0,52447

5	-1	-1	84,23	0,93021	0,52272
5	-1	-0,5	82,99	0,92668	0,52077
5	-1	3	73,67	0,90161	0,51061
5	-1	2,5	75,16	0,90651	0,51167
5	-1	2	76,36	0,90965	0,51277
5	-1	1,5	77,8	0,91318	0,51423
5	-1	1	79	0,91642	0,51578
5	-1	0,5	80,45	0,92047	0,5176
5	-1	0	81,64	0,92348	0,51898
5	-0,5	-3	89,05	0,94411	0,52127
5	-0,5	-2,5	87,72	0,94115	0,519
5	-0,5	-2	86,2	0,93738	0,51715
5	-0,5	-1,5	84,95	0,9342	0,51527
5	-0,5	-1	83,56	0,93022	0,5138
5	-0,5	-0,5	82,38	0,92712	0,51226
5	-0,5	3	72,98	0,90183	0,50052
5	-0,5	2,5	74,51	0,90666	0,50313
5	-0,5	2	75,74	0,90995	0,50474
5	-0,5	1,5	77,2	0,91359	0,50633
5	-0,5	1	78,38	0,91671	0,50712
5	-0,5	0,5	79,81	0,92067	0,50875
5	-0,5	0	81,01	0,92378	0,51046
5	3	-3	84,84	0,94658	0,46195
5	3	-2,5	83,63	0,94362	0,46092
5	3	-2	82,24	0,94017	0,45931
5	3	-1,5	81,08	0,93743	0,45795
5	3	-1	79,67	0,93342	0,45611
5	3	-0,5	78,5	0,93059	0,4545
5	3	3	69,25	0,9051	0,44257
5	3	2,5	70,64	0,90909	0,44498
5	3	2	71,9	0,91302	0,44708
5	3	1,5	73,32	0,91744	0,44872
5	3	1	74,51	0,92057	0,44989
5	3	0,5	75,95	0,9241	0,4515
5	3	0	77,12	0,92719	0,45312
5	2,5	-3	85,47	0,94609	0,47058
5	2,5	-2,5	84,21	0,94302	0,4694
5	2,5	-2	82,82	0,93955	0,46797
5	2,5	-1,5	81,67	0,93674	0,46675
5	2,5	-1	80,26	0,93255	0,46526
5	2,5	-0,5	79,11	0,92969	0,46403
5	2,5	3	69,86	0,90447	0,45328
5	2,5	2,5	71,26	0,90842	0,45505
5	2,5	2	72,49	0,91264	0,45602
5	2,5	1,5	73,91	0,91674	0,45775

5	2,5	1	75,13	0,9197	0,45966
5	2,5	0,5	76,56	0,92337	0,4612
5	2,5	0	77,72	0,92645	0,46216
5	2	-3	86,06	0,94582	0,47961
5	2	-2,5	84,74	0,94275	0,47726
5	2	-2	83,3	0,93914	0,47473
5	2	-1,5	82,13	0,93644	0,47316
5	2	-1	80,71	0,9322	0,47163
5	2	-0,5	79,58	0,9293	0,47049
5	2	3	70,34	0,90391	0,46152
5	2	2,5	71,75	0,90787	0,46321
5	2	2	73	0,91228	0,46434
5	2	1,5	74,4	0,91609	0,46564
5	2	1	75,62	0,91922	0,46664
5	2	0,5	77	0,92291	0,46771
5	2	0	78,21	0,92615	0,46889
5	1,5	-3	86,78	0,94546	0,49014
5	1,5	-2,5	85,41	0,94208	0,48804
5	1,5	-2	84	0,93849	0,48646
5	1,5	-1,5	82,77	0,93568	0,48322
5	1,5	-1	81,32	0,93159	0,48049
5	1,5	-0,5	80,16	0,92863	0,47903
5	1,5	3	70,92	0,90344	0,47028
5	1,5	2,5	72,32	0,90749	0,47141
5	1,5	2	73,58	0,91197	0,47252
5	1,5	1,5	75,01	0,91552	0,47385
5	1,5	1	76,2	0,91863	0,47474
5	1,5	0,5	77,58	0,92229	0,47609
5	1,5	0	78,79	0,9255	0,4773
5	1	-3	87,3	0,94504	0,49758
5	1	-2,5	85,96	0,94173	0,49606
5	1	-2	84,52	0,93814	0,49417
5	1	-1,5	83,34	0,9353	0,49226
5	1	-1	81,89	0,93095	0,49017
5	1	-0,5	80,69	0,92803	0,48778
5	1	3	71,41	0,90293	0,4774
5	1	2,5	72,81	0,90719	0,4784
5	1	2	74,05	0,91155	0,47943
5	1	1,5	75,49	0,91511	0,48051
5	1	1	76,67	0,91818	0,4813
5	1	0,5	78,09	0,92175	0,48374
5	1	0	79,3	0,92501	0,48513
5	0,5	-3	87,96	0,94476	0,50586
5	0,5	-2,5	86,59	0,94152	0,50465
5	0,5	-2	85,14	0,93775	0,50293

5	0,5	-1,5	83,96	0,93487	0,50165
5	0,5	-1	82,54	0,93047	0,49999
5	0,5	-0,5	81,37	0,9275	0,49813
5	0,5	3	71,99	0,90239	0,48592
5	0,5	2,5	73,44	0,90666	0,48767
5	0,5	2	74,66	0,91075	0,48875
5	0,5	1,5	76,12	0,91445	0,49002
5	0,5	1	77,34	0,91767	0,49155
5	0,5	0,5	78,74	0,92127	0,49352
5	0,5	0	79,97	0,92441	0,49564
5	0	-3	88,48	0,94449	0,51331
5	0	-2,5	87,12	0,94131	0,51157
5	0	-2	85,66	0,93753	0,51013
5	0	-1,5	84,46	0,9346	0,50838
5	0	-1	83,03	0,93024	0,50658
5	0	-0,5	81,87	0,92738	0,5052
5	0	3	72,46	0,90209	0,49295
5	0	2,5	73,96	0,90675	0,49457
5	0	2	75,18	0,91042	0,49646
5	0	1,5	76,66	0,91403	0,49821
5	0	1	77,89	0,91724	0,50038
5	0	0,5	79,3	0,92085	0,50189
5	0	0	80,49	0,92398	0,50304
x2	-3	-3	145,16	0,94584	0,56186
x2	-3	-2,5	143,03	0,9427	0,5605
x2	-3	-2	140,33	0,93895	0,55895
x2	-3	-1,5	138,07	0,9356	0,55748
x2	-3	-1	135,53	0,93168	0,55443
x2	-3	-0,5	133,43	0,92752	0,55198
x2	-3	3	118,19	0,9018	0,53743
x2	-3	2,5	120,78	0,90627	0,53913
x2	-3	2	122,9	0,90908	0,54165
x2	-3	1,5	125,18	0,91265	0,54421
x2	-3	1	127,12	0,9163	0,54602
x2	-3	0,5	129,37	0,92009	0,54794
x2	-3	0	131,15	0,92314	0,54952
x2	-2,5	-3	143,97	0,94617	0,55249
x2	-2,5	-2,5	141,79	0,94308	0,55131
x2	-2,5	-2	139,09	0,93951	0,54849
x2	-2,5	-1,5	136,7	0,93569	0,54603
x2	-2,5	-1	134,34	0,93203	0,54409
x2	-2,5	-0,5	132,31	0,92742	0,54249
x2	-2,5	3	117,1	0,90192	0,52924
x2	-2,5	2,5	119,67	0,90669	0,53089
x2	-2,5	2	121,74	0,90976	0,53193

x2	-2,5	1,5	124	0,91317	0,53337
x2	-2,5	1	125,93	0,91662	0,5352
x2	-2,5	0,5	128,32	0,92054	0,53871
x2	-2,5	0	130,13	0,92345	0,54058
x2	-2	-3	142,97	0,9465	0,54384
x2	-2	-2,5	140,69	0,94342	0,54223
x2	-2	-2	138,08	0,93957	0,54003
x2	-2	-1,5	135,75	0,93579	0,53842
x2	-2	-1	133,49	0,93228	0,53655
x2	-2	-0,5	131,46	0,92762	0,5351
x2	-2	3	116,2	0,90219	0,52158
x2	-2	2,5	118,73	0,90685	0,5237
x2	-2	2	120,86	0,91011	0,52524
x2	-2	1,5	123,15	0,91346	0,52642
x2	-2	1	125,05	0,91689	0,52796
x2	-2	0,5	127,37	0,92089	0,52992
x2	-2	0	129,22	0,92382	0,53183
x2	-1,5	-3	141,72	0,94678	0,5341
x2	-1,5	-2,5	139,5	0,94365	0,53284
x2	-1,5	-2	136,9	0,93962	0,53136
x2	-1,5	-1,5	134,66	0,93613	0,52943
x2	-1,5	-1	132,35	0,93257	0,52583
x2	-1,5	-0,5	130,33	0,92817	0,5244
x2	-1,5	3	115,14	0,90244	0,51339
x2	-1,5	2,5	117,57	0,90687	0,51476
x2	-1,5	2	119,76	0,91051	0,51677
x2	-1,5	1,5	122,13	0,91399	0,51804
x2	-1,5	1	124,05	0,91726	0,51969
x2	-1,5	0,5	126,31	0,92118	0,52108
x2	-1,5	0	128,16	0,9243	0,52239
x2	-1	-3	140,81	0,94701	0,52747
x2	-1	-2,5	138,54	0,94375	0,52548
x2	-1	-2	135,88	0,93981	0,52261
x2	-1	-1,5	133,72	0,93635	0,52093
x2	-1	-1	131,53	0,93287	0,51911
x2	-1	-0,5	129,55	0,92841	0,51783
x2	-1	3	114,34	0,9028	0,507
x2	-1	2,5	116,73	0,90704	0,50841
x2	-1	2	118,84	0,91061	0,50953
x2	-1	1,5	121,31	0,91428	0,51136
x2	-1	1	123,23	0,91743	0,51294
x2	-1	0,5	125,49	0,92137	0,5146
x2	-1	0	127,39	0,92455	0,51622
x2	-0,5	-3	139,62	0,94742	0,51769
x2	-0,5	-2,5	137,35	0,9439	0,51579

x2	-0,5	-2	134,77	0,93987	0,51464
x2	-0,5	-1,5	132,7	0,93644	0,51271
x2	-0,5	-1	130,56	0,93309	0,51096
x2	-0,5	-0,5	128,59	0,92869	0,50958
x2	-0,5	3	113,18	0,90311	0,49569
x2	-0,5	2,5	115,58	0,90756	0,4982
x2	-0,5	2	117,75	0,91124	0,50028
x2	-0,5	1,5	120,24	0,91467	0,50306
x2	-0,5	1	122,19	0,91783	0,50407
x2	-0,5	0,5	124,48	0,92179	0,50594
x2	-0,5	0	126,36	0,92484	0,50749
x2	3	-3	132,8	0,95	0,45832
x2	3	-2,5	130,48	0,94602	0,4569
x2	3	-2	128,23	0,94269	0,45515
x2	3	-1,5	126,44	0,94	0,45363
x2	3	-1	124,27	0,93688	0,45168
x2	3	-0,5	122,21	0,93243	0,44938
x2	3	3	107	0,90731	0,43528
x2	3	2,5	109,32	0,9115	0,43768
x2	3	2	111,25	0,91455	0,44041
x2	3	1,5	113,73	0,91951	0,44329
x2	3	1	115,7	0,92282	0,44462
x2	3	0,5	118,03	0,92607	0,44626
x2	3	0	120,05	0,92924	0,44778
x2	2,5	-3	133,78	0,94945	0,46735
x2	2,5	-2,5	131,54	0,9454	0,46602
x2	2,5	-2	129,18	0,94189	0,46447
x2	2,5	-1,5	127,42	0,9392	0,46301
x2	2,5	-1	125,26	0,93623	0,46084
x2	2,5	-0,5	123,22	0,93163	0,45924
x2	2,5	3	108,08	0,90652	0,44733
x2	2,5	2,5	110,34	0,91052	0,44919
x2	2,5	2	112,26	0,91384	0,45086
x2	2,5	1,5	114,68	0,91881	0,45242
x2	2,5	1	116,68	0,92187	0,45401
x2	2,5	0,5	119,04	0,92525	0,45594
x2	2,5	0	120,99	0,92829	0,45675
x2	2	-3	134,7	0,94902	0,47628
x2	2	-2,5	132,49	0,9454	0,47388
x2	2	-2	129,92	0,9412	0,4711
x2	2	-1,5	128,14	0,93875	0,46959
x2	2	-1	126,03	0,93563	0,46791
x2	2	-0,5	124,02	0,93102	0,46695
x2	2	3	108,87	0,90598	0,45547
x2	2	2,5	111,11	0,90972	0,45731

x2	2	2	113,1	0,91365	0,45888
x2	2	1,5	115,48	0,91811	0,4604
x2	2	1	117,48	0,92124	0,46151
x2	2	0,5	119,87	0,92458	0,46323
x2	2	0	121,83	0,92775	0,46475
x2	1,5	-3	135,87	0,94854	0,48706
x2	1,5	-2,5	133,67	0,94496	0,48496
x2	1,5	-2	131,05	0,94067	0,48254
x2	1,5	-1,5	129,13	0,9379	0,47921
x2	1,5	-1	127,02	0,93508	0,47671
x2	1,5	-0,5	124,97	0,93029	0,47566
x2	1,5	3	109,83	0,90525	0,46506
x2	1,5	2,5	112,06	0,90907	0,46651
x2	1,5	2	114,1	0,91327	0,46774
x2	1,5	1,5	116,47	0,91721	0,46943
x2	1,5	1	118,54	0,92037	0,47081
x2	1,5	0,5	120,92	0,92389	0,47251
x2	1,5	0	122,81	0,927	0,47398
x2	1	-3	136,75	0,94819	0,49457
x2	1	-2,5	134,6	0,94482	0,49288
x2	1	-2	131,95	0,9403	0,49108
x2	1	-1,5	130,03	0,93746	0,48853
x2	1	-1	127,89	0,9346	0,48537
x2	1	-0,5	125,77	0,92982	0,48322
x2	1	3	110,59	0,90471	0,47226
x2	1	2,5	112,85	0,9087	0,47386
x2	1	2	114,93	0,91296	0,47515
x2	1	1,5	117,31	0,91653	0,47678
x2	1	1	119,34	0,91982	0,47754
x2	1	0,5	121,72	0,92341	0,47982
x2	1	0	123,6	0,92652	0,48097
x2	0,5	-3	137,8	0,94775	0,50323
x2	0,5	-2,5	135,7	0,9446	0,50215
x2	0,5	-2	133	0,93997	0,50024
x2	0,5	-1,5	131,08	0,93692	0,49849
x2	0,5	-1	128,94	0,93384	0,49632
x2	0,5	-0,5	126,94	0,92918	0,49499
x2	0,5	3	111,55	0,90402	0,48095
x2	0,5	2,5	113,87	0,90802	0,48308
x2	0,5	2	115,96	0,91246	0,48414
x2	0,5	1,5	118,36	0,91596	0,48566
x2	0,5	1	120,4	0,91925	0,48673
x2	0,5	0,5	122,71	0,9228	0,48904
x2	0,5	0	124,65	0,92585	0,49108
x2	0	-3	138,7	0,94766	0,51047

x2	0	-2,5	136,52	0,94425	0,50881
x2	0	-2	133,87	0,93998	0,5075
x2	0	-1,5	131,89	0,93667	0,50544
x2	0	-1	129,72	0,93348	0,50322
x2	0	-0,5	127,76	0,92904	0,50216
x2	0	3	112,33	0,90365	0,48779
x2	0	2,5	114,68	0,90783	0,48973
x2	0	2	116,82	0,91201	0,49165
x2	0	1,5	119,25	0,91528	0,49363
x2	0	1	121,35	0,91856	0,49617
x2	0	0,5	123,64	0,92208	0,49849
x2	0	0	125,54	0,9252	0,49996