AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE
WYDZIAŁ ENERGETYKI I PALIW

KATEDRA ZRÓWNOWAŻONEGO ROZWOJU ENERGETYCZNEGO

Master thesis

„Agent-based modeling of electricity markets”
"Modelowanie rynków energii elektrycznej oparte na agentach"

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Kraków, *2023*

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Abstract

In the following thesis three computer applications simulating electricity markets in Poland were created and tested on them. The research model covered the period from 01.06.2022 to 31.05.2023. The model was built on the basis of daily reports of national power demand and generation from various sources based on the databases of the Polish Power Grid. In addition, the most important strategic documents for the Polish Energy Sector were taken into account. Analytical and graphical elaboration of the results was carried out based on the Python programming language and function libraries available in it. Its results were validated with an analogous model, developed using the commercial programming language GAMS. Various situations that could occur in the Polish electricity market were simulated and several scenarios developed by experts were tested. Archival data from the period under study on energy demand, energy prices, and key fuels in Poland and around the world were studied The volatility of energy prices in relation to the situation in the day-ahead and balancing markets was examined. Various variants of price stacks (merit order system) of the Polish energy mix were developed. The analysis of the results made it possible to observe the influence of various factors, i.e. technological, climatic, economic, and social factors on the level of energy prices.

Streszczenie

W ramach poniższej pracy stworzono trzy aplikacje komputerowe symulujące rynki energii elektrycznej w Polsce oraz przeprowadzono na nich badania. Model badawczy obejmował okres od 01.06.2022 do 31.05.2023. Model zbudowany został na podstawie raportów dobowych krajowego zapotrzebowania na moc oraz generacji energii z różnych źródeł w oparciu o bazy danych Polskich Sieci Elektroenergetycznych. Dodatkowo wzięto pod uwagę najważniejsze dokumenty strategiczne dla Polskiej Energetyki. Opracowanie analityczne i graficzne wyników wykonane zostało w oparciu o język programowania Python oraz dostępnych w nim bibliotek funkcji. Jego wyniki zostały zwalidowane za pomocą analogicznego modelu, opracowanego przy wykorzystaniu komercyjnego języka programowania GAMS. Zasymulowano różne sytuacje mogące wystąpić na Polskim rynku energii elektrycznej oraz sprawdzono kilka opracowanych przez ekspertów scenariuszy. Prześledzono dane archiwalne z badanego okresu dotyczące zapotrzebowania na energię, cen energii i kluczowych paliw w Polsce i na świecie. Zbadano zmienność cen energii w zależności od sytuacji na rynku dnia następnego oraz na rynku bilansującym. Opracowano różne warianty stosów cenowych (system merit order) Polskiego miksu energetycznego. Analiza wyników pozwoliła na zaobserwowanie wpływu różnych czynników tj. technologicznych, klimatycznych, gospodarczych i społecznych na poziom cen energii.

1 Introduction

Since the beginning of their existence, people have sought to satisfy all their needs. Since they are unable to produce all the goods they need, in order to have easy access to them, markets and then money were created. Since ancient times, the market was a meeting place for people who wanted to exchange their goods for other goods (more useful to them) or for money. First local markets were created and their participants were, for example, residents of a village or small town. Then, with the development of civilization, the markets grew [1]. More and more international merchants traveling along the established commodity routes appeared on them. The products sold in the markets were increasingly exotic and luxurious. This allowed for a general increase in the standard of living of the population. International trade had (and still has) another important task. It allowed for a general reduction in the prices of goods and their greater availability. The interstate and intercontinental flow of goods meant that customers began to have choices. If domestic production became unprofitable relative to the price of goods imported from abroad, they could buy them more cheaply. Thus, money that would have been unnecessarily spent on overpaying for a product could support another branch of the economy (and people began to get richer, because instead of buying one product, they could buy several and satisfy more of their needs) [2]. The key in this situation, therefore, was international exchange, without which countries could not have developed at such a rapid pace and their inhabitants would have had access only to the basic commodities that a particular location of residence could offer them. Thus, in a nutshell, I have presented the method of formation of markets, as well as their essence and key participants. Today's commodity markets are highly developed. International cooperation in the exchange of goods is at a very high level, often a few clicks of the mouse on a computer screen to, for example, order items to Poland from distant China or the USA.

1.1 Energy market - historical brief

The picture I outlined in the previous chapter of the market as a place for the exchange of goods has evolved over the years. Today, we can talk about the market as a place but also as a virtual space that brings together sellers and buyers. Anyone can create an offer to sell or buy goods. Physically, the interested parties can be very far from each other, and often this is no barrier to a transaction. The origins of energy markets (actually the electric power industry itself) date back more than 100 years, but their rapid development did not occur until after World War II [3]. For most of the 20th century when consumers wanted to buy energy they could not choose their supplier [4]. The structure of these markets was highly centralized and perniciously monopolistic. Most often, it remained under the full control of governments. This was partly due to the pattern of how States operated during the war, where they had full control over the economy (and the energy market was strategically probably the most important area) and also because any investment in energy, transmission networks and power plants was (and is) extremely expensive. It was easier for large monopolistic companies to survive and grow, even if prices and vendor margins were high and the price of energy varied widely in different areas. As technology evolved, the thesis energy market evolved. Economists began to argue that a monopoly removes the incentive to operate efficiently and allows plants to invest unnecessarily. Then the costs of mistakes made by large corporations would be passed on to consumers [4]. Over time, new opportunities also emerged, for example, for the international sale of energy, or at least the efficient transmission of energy over long distances. The first country where privatization of the electricity sector was allowed was Great Britain. There, in 1989, a piece of legislation called the "Electricity Act" was enacted, which caused the collapse of the monopolistic CEGB organization. This allowed the introduction of competition in such sectors as energy generation, transmission and distribution (the three most important areas for the power industry) [3]. The political changes that took place in Europe after 1989 [5] (the beginning of the collapse of European communism and the aspiration of the countries affected by it to democracy) also affected the electric power industry, pushing the sector toward decentralization and opening the door to international trade.

Since then, we can talk about electricity as a commodity (on which the whole world depends), the "place" of its sale as a market and its participants who are producers, sellers and consumers of energy. A turning point for Poland was the entry into force of the "Energy Law" regulating the energy market (I will discuss this in detail in the following chapters). The abolition of monopolies and the State's exclusive control over this sector allowed the market to become competitive. This has made it possible to provide much lower (regulated by market mechanisms and not government-controlled) energy prices for energy buyers and also allows cooperation and larger areas for the producers to sell the product. The same thing has happened with energy as with other commodities in the markets whose evolution was outlined in the introduction. The laws of the market are indisputable. It is clear that for such a strategically important product as electricity, only international cooperation and fair competition can provide society with cheap electricity. It is an essential fuel for the country, enabling the country to develop freely and intensively and society to live at a high level of satisfaction. Since the dawn of history, the laws of markets have pushed them to the model that has been formed today. The possibility of energy flow between the borders of countries and continents, the comfort of consumers who decide for themselves about their energy supplier or large international energy markets controlled by sophisticated algorithms optimizing its price. These are the main topics I would like to address in the following paper. I would like to discuss the mechanics of the Polish energy market compared to the European one and the methods of determining the most favorable market price. I will also mention how these markets interconnect and its stages (day-ahead, spot and balancing markets) that lead to meeting the country's energy needs.

1.2 What is an energy market ?

1.2.1 Energy market goal

"The overriding goal of the electricity market is to ensure reasonable prices, reliable supplies of energy with high quality parameters, and to guarantee the market profitability of entities operating in the electric power industry" [6].

The electricity market is significantly different from other commodity markets. We can treat electricity as a good while its physical structure is very unique. Electricity should not be viewed as just MWh. Its price also consists of :

- Line capacity (and the losses resulting from it)
- flexibility (the parameters of electricity are not constant - they change all the time depending on the demand for it and the supply of it in the market - because we do not know how to store it efficiently) [7].

In summary, electricity has different parameters depending on when and where it is produced, sold and distributed.

The most important features of the Electricity Market are [8]:

- Impossibility of direct observation using the senses (it is a virtual market);
- Impossibility of effective storage (of course, there are methods for periodic storage, however, at present they cannot yet be used on a large scale - so it is assumed to be a real-time market);
- The product is mainly electricity (trading of emission permits or energy raw materials is also allowed);
- Versatility of use of the product - electricity is used in virtually every area of the economy and everyday life; consumers depend on it and it is a pillar of State security;
- Limited substitutability of the product of the main market;
- The market must operate continuously (the need to constantly compensate for the demand and supply of energy);
- We cannot completely control this market because the supply of energy changes unpredictably all the time (one can only create models to simulate consumer behavior but they will never be 100% accurate) [7];
- The market and its participants are limited by the limits of the transmission networks of this good [7];
- High strategic and economic importance for you - it is very sensitive to changes in demand and supply; even small unbalanced fluctuations between the two can cause huge financial and economic losses [7];
- Large fluctuations in the supply of the good; in the event of an energy shortage in the market, new suppliers may be ready to serve even after only a few hours (that's how long it takes for a conventional power plant to start up) [7];

The implementation of the electricity market was intended to separate the product and its producers from the network suppliers. The key elements of the market are as follows:

- Energy production
- Transmission and distribution
- Coordination of supply and demand

In this way, the price of energy for the consumer is kept as low as possible because it can be shaped separately at each stage of its transmission.

Due to the above outlined characteristics of the energy market and electricity itself, the idea of creating several markets working together was born. They control its distribution even from several years back to the very moment of delivery. This allows for greater energy security of the country and a quick response in situations of shortage or overproduction of energy in the market.

1.2.2 Basic structure of the energy transmission and distribution system

The energy system can be compared to the nervous system in the human body. At the heart of the system are power plants that generate energy. Transmission networks then distribute it to the various organs just like arteries in the human body. How much energy flows in which direction is supervised by the Transmission System Operator. It watches over the balance between energy supply and demand. The next stage is a network of lower voltage lines (distribution system) that transmit energy to large and smaller consumers. Just as the nervous system distributes blood throughout the human body. A diagram of a simple energy system is shown in Figure 1.1.

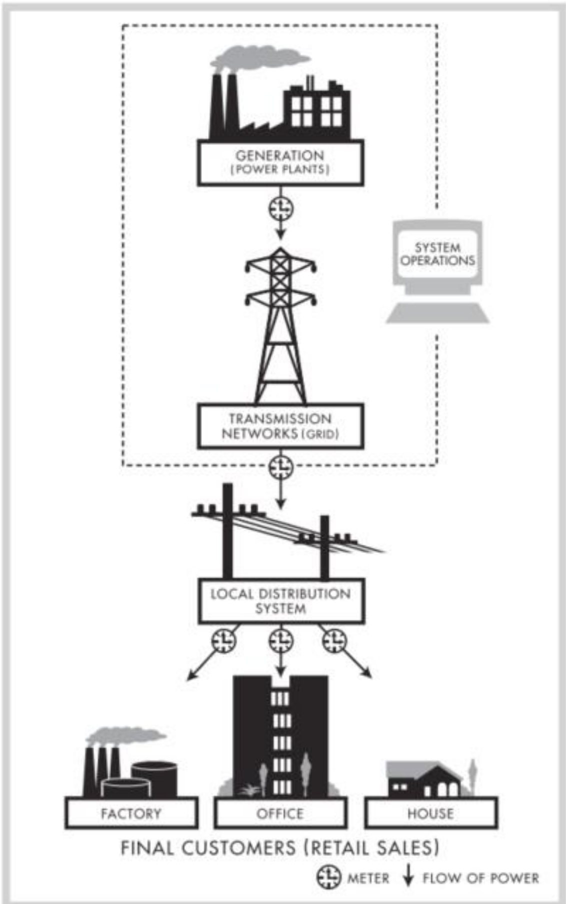


Figure 1.1 - Basic scheme of electricity system [9]

1.3 General division of energy markets

Both in Poland and throughout the European Union, we have a very similar system of dividing energy markets and their interaction. As we can see in Figure 1.2, we divide markets mainly according to the "stage at which the energy is" (whether we are trading power, transmission or trying to balance it in the market) and according to how early before delivery we transact.

In my deliberations, I further distinguished markets according to their area of operation, structure and customers.

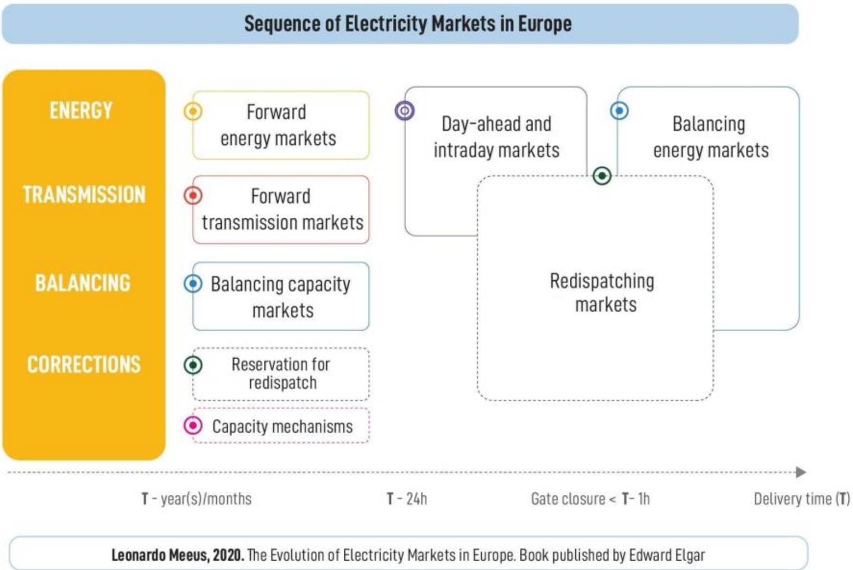


Figure 1.2 - Sequence of Electricity Markets in Europe [7]

1.3.1 Structural

Monopoly

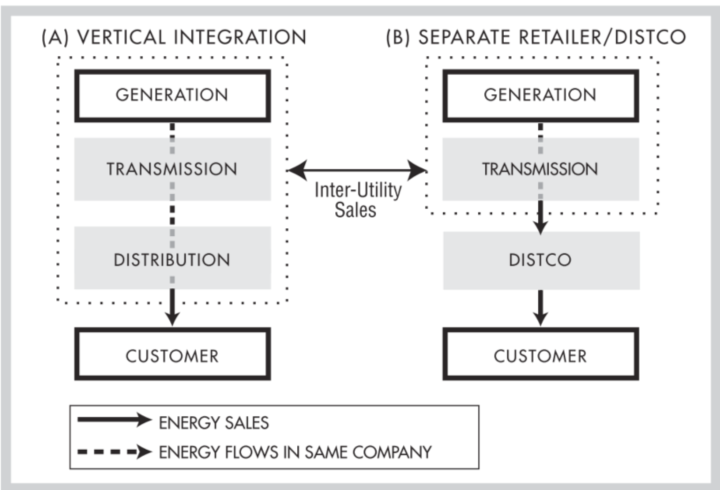


Figure 1.3 - Diagram of the energy market in the monopoly type [9]

A monopolistic energy system (Figure 1.3) is when both the generation of energy its transmission and distribution is controlled by one company. Customers then have no choice but to buy electricity from this supplier even when the offer is unfavorable to them. In addition, the supplier can dictate arbitrary prices because there is no competition and electricity is a primary commodity. On the other hand, it can offer energy more cheaply than small businesses because the more of a good it generates, as a rule, its unit price is lower.

Single Buyer

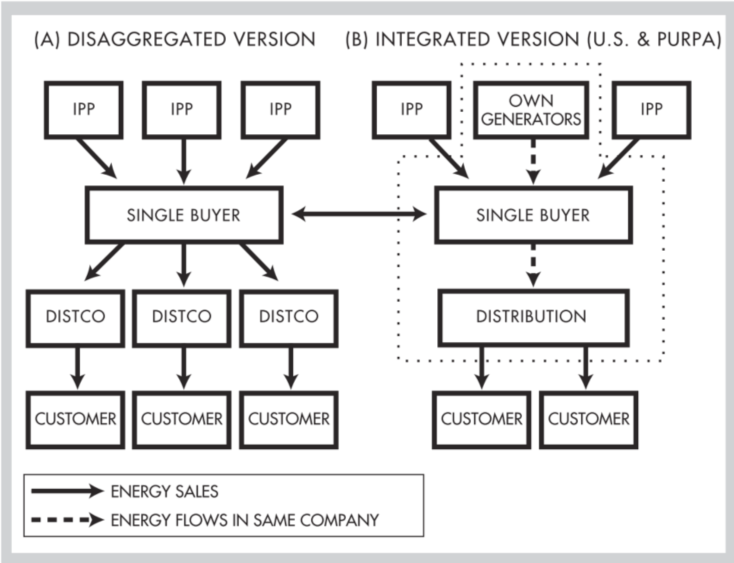


Figure 1.4 - Diagram of the energy market in the "single buyer" type [9]

The single buyer system (Figure 1.4) is quite different from monopoly. First of all, it allows generation other than its own units. Depending on its type, it deals with both buying energy and distributing it, or only generating and distributing it among distributors. In this case, citizens have a choice of who they want to buy energy from in the end and can choose a convenient deal for themselves.

Perfect competition

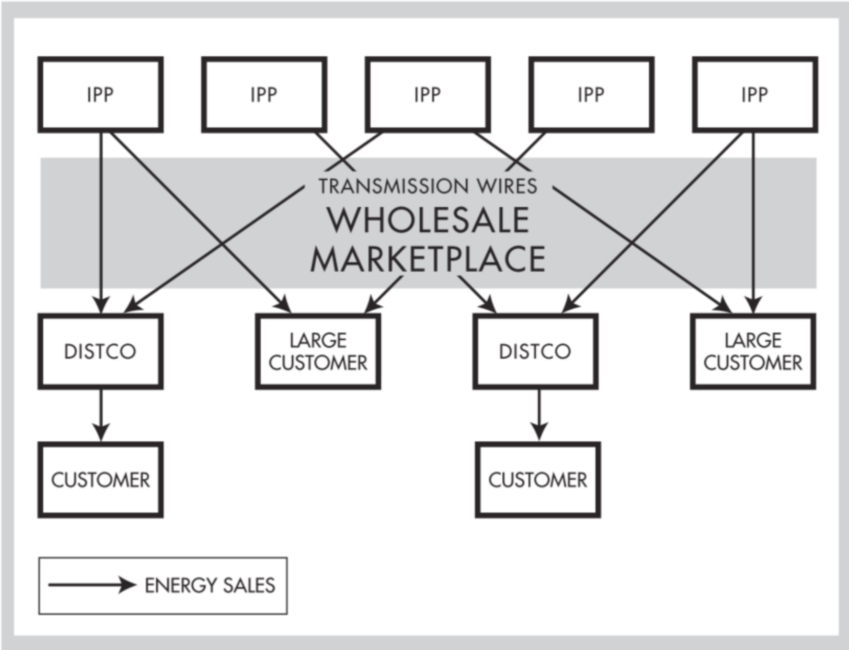


Figure 1.5 - Diagram of the energy market in the type of perfect competition [9]

The last of the most popular types of energy systems is perfect competition. Such a scheme is used by Poland and a great many countries around the world, among others. It consists in that no part of the market is strictly controlled by one company. Anyone who owns a power plant can sell energy on a market from which many distributors can buy it back. Direct participation is also allowed from the market by buyers from large companies, who purchase large volumes of energy. This allows them to purchase it more cheaply and use the rest of the funds to expand their business.

1.3.2 By market participants

Wholesale market

Participants in this market include power producers as well as wholesale buyers and very large retail buyers (due to the rather complicated market entry process and the need to balance electricity on their own) [8].

Retail Market

A lower level of the energy market is available to small end users, such as households and small and medium-sized enterprises. In this market, the sellers are distribution companies. Sellers can compete with each other on price, range of services or delivery terms. In Poland, for example, each household can choose its own energy supplier according to its own preferences.

1.3.3 Due to the time area covered - the time from purchase to execution of the transaction

In the electricity grid, it is necessary for supply and demand to be in balance at all times, due to the need for continuous supply of energy to consumers. The two most important stages of trading are the day-ahead market (SPOT type) and the balancing market [10].

All day-ahead markets close one hour before delivery as opposed to the spot market [10].

Long-Term Markets

A market where contracts are traded as far back as four years to one month before delivery. Trading can take place through a financial exchange or the market parties can enter into over the counter (OTC) deals. If there is an international market then the established prices are then converted according to bidding zone boundaries, which usually coincide with national borders.

The Day-Ahead Market

Includes energy trading from 24 hours to 2 hours before delivery [11]. All accepted bids are paid based on the marginal bid.

Intraday Market

Energy trading on a given day (happens one hour before delivery) [10]. Follows settlement of the day-ahead market [11]. The balancing market is the responsibility of the TSO.

Balancing Market

It follows the close of trading in the intraday market. All differences, between energy demand and supply, must be adjusted in the real-time balancing market [10].

We can divide balancing markets into two types [11]:

- **Balancing Power Market**

Participants in this market are Balancing Service Providers (BSPs) who sell the "availability" of their units. They get paid for declaring their willingness to generate energy at specific times and dates. Contracts are made a year in advance up to one day before delivery.

- **Balancing Energy Market**

Participants in the power market who have declared their availability at the appropriate time bid for balancing energy. How much energy will be bought or sold here at any given time depends on the imbalance of the system in real time.

1.3.4 By area of operation

Domestic markets

A system of energy markets operating within a single country. It may happen that the country is divided into different bidding zones and price zones, but most often it is a unified area under the control of one TSO.

International markets

An example of an energy market operating internationally is the model of coupling European energy markets. This is of great strategic importance and increases the energy security of individual States but also of the continent as a whole.

Bidding zones in Europe as seen on the map in Figure 1.6 are mostly in line with State borders. Exceptions are a few States such as Norway, Finland, Denmark and Italy where the country is further divided into smaller zones. Additionally, Germany is treated with Luxembourg as one zone [11].

Figure 1.6 - The bidding zone configuration in Europe in July 2021 [11]

Ultimately, the goal in Europe is to connect national markets in such a way that bidding zones are determined according to the capacity of power lines and the energy demand of individual countries rather than national borders [11].

European Long Term Market

If a market participant wants to secure prices in different bidding zones, long-term inter-zonal transmission rights must be purchased separately on a special Joint Allocation Office (JAO) platform. This is a common platform of transmission system operators. In contrast, the document governing the allocation and calculation of inter-zonal transmission rights is the Forward Capacity Allocation Guideline (FCA GL).

In addition, it is possible for member states to establish a capacity trading mechanism. It can take various forms, operate from one to four years prior to delivery and be organized by the TSO [11].

European Day-Ahead Market

The day-ahead market consists of one pan-European auction at noon for 24 hours the following day. Trading is organized by one or more energy exchanges in each member state.

European Intra-Day Market

Currently, this market is traded continuously (according to mechanisms identical to those of stock exchanges) in some countries and through auctions in other countries. It was recently decided that in the next few years the model of this market will consist of three pan-European auctions at predetermined times [11].

European Balancing Market

Real-time energy balancing is the responsibility of TSOs, each according to their area of operation [11].

1.4 Basic terms

Real-time market – a market in which the demand for a product is met virtually instantaneously, at any time; e.g., an electricity market that must constantly balance and meet fluctuating demand for electricity.

Bidding zone – is a geographic area within which market participants can exchange electricity without prior allocation of power.

PSCMI (Polish Steam Coal Market Index) – these are price indices for benchmark thermal coal produced by domestic producers and sold in the domestic power market [12]; these indices take into account the selling price of coal excluding excise taxes, at the point of loading, excluding insurance costs and the cost of delivery on the main transportation route [12].

Discount rate – a factor used to calculate the future value of capital due to the fluctuating value of money over time 13].

1.5 Literature review

I would like to mention and outline in a few words the works and projects that address the various aspects I have studied.

1.5.1 "Merit Order and Marginal Abatement Cost Curve in Python"

In the paper "Merit Order and Marginal Abatement Cost Curve in Python," its author Himalaya Bir Shrestha simulated a merit order model using the Python language. While he did not include optimization, he focused on the relationship between the merit order curve and how to assess the cost-effectiveness of decarbonization in a country, region or organization based on the marginal abatement cost curve. This allows one to see the impact of merit order on the wholesale price of electricity and how the Marginal Abatement Cost curve shapes up.

The author noted that the introduction of merit order in the EU was influenced by two factors: the desire to minimize the cost of electricity and to reduce CO_2 emissions from power plants (increasing the share of RES in the energy mix). In the material, he discussed how the combination of renewable energy and fossil fuels in a country's power system portfolio affects its price - random data but it's all about methodology. He also briefly discussed the basic concepts involved.

In the work above, Marginal Abatement Cost measures the cost of reducing one additional unit of CO_2 emissions. While the merit order curve is based on the ordering of technologies by marginal production cost, the Marginal Abatement Cost (MAC) curve is based on the ordering of different mitigation options in CO_2

emissions. On the MAC curve, the width of the bar represents the greenhouse gas (GHG) emission reduction potential of each technology or option. This also makes it possible to calculate the savings after implementing certain retrofits that reduce CO_2 reductions.

The conclusion of the above work is that:

- The price of electricity depends on a country's energy demand and its energy mix. When demand increases, more power plants on the right side of the graph (more expensive) must be turned on, which increases the clearing price, and vice versa. If there is more renewable power plant capacity available in the portfolio, more of the demand is met by them and this results in a lower electricity price – the merit order effect.
- The MAC curve makes it possible to compare energy used in different sectors (energy, transportation, buildings, forestry and waste). It provides a key initial assessment of the potential and cost-effectiveness of various mitigation options.

1.5.2 "Energy Transition Game"

Another very interesting project is the board game "Energy Transition Game". Its author is the "games4sustainability" team. The game is very large, designed for a minimum of a dozen people. It is led by trained facilitators who teach the game in several countries to educate the community. I myself had the pleasure of taking part as a participant in this predevelopment.

The purpose of the game is (like mine) to show the interconnectivity of energy markets and to show the roles of the various decision makers (in addition with random events affecting gameplay). The game is divided into turns where each turn is divided into 4 seasons (seasons). Conventional power plants operate all year round and renewable ones, for example, like solar only for 3 seasons. This is an added complication in the game. Every turn our society develops. There is an increase in energy demand and the most important indicator. The degree of climate pollution. When it reaches the maximum level the game is over. Climate pollution is Increased by conventional power plants so in order to survive you have to strive for RES.

During training, each player takes on a different role in a complex energy system. Each role has its own set of decisions and responsibilities:

- Energy producers– seek to maximize their profits while minimizing environmental damage. However, if they ignore this threat the game will quickly climatic disasters will result.
- Sturt- ups - are bringing clean energy technologies to market. They take an investment risk simulated by a throw of the dice. Games they manage to buy new technology they can resell it to energy producers and distributor. This can include sponges that absorb pollution from conventional power plants or energy storage for the entire system.
- The energy distributor - balances the changing demand and supply of energy. He is the most important person in the game. His job is to steer the system so that at the end of each round in each season the system is perfectly balanced– punished both by a blackout caused by a shortage of energy in the grid and by overloading it with too much production, for example, in the summer.
- Government– a trio of politicians- who set the price for energy at the same time taking care of their support in the community;
- Side characters– various community members who care about the welfare of employees and consumers of power plants, or journalist who help the government (they can impose penalties on them).

The big advantage of this type of game is all players can freely interact with each other, create agreements, introduce new policies together, and test new out-of-the-box solutions.

1.5.3 "Building a day-ahead electricity market" laboratory report, DTU, 31761 Renewables in Electricity Markets

This publication presents a description of a credit project by Danish students: Sigurd Indrehus, Lorenzo Mininni and Jorge Montalvo Arvizu. The subject is Renewables in Electricity Markets. The goal of the project was to understand how the day-ahead market concept and the energy price matching system, Merit Order, works.

The solution was modeled as a linear program in the Julia optimization language. The model included the objective function and constraints and was presented in a compact form using matrices and vectors . They included the distribution of unit generation in each zone and billing hour, with the added assumption that they must be positive and non-zero. Moreover, a limit was set on the transmission of energy between the two Danish regions. The objective function was to minimize the total cost of energy, which was equal to maximizing social welfare. In this model, there are no demand bids (there is only one demand to be satisfied).

The prorgam simulated two days in 2019/20 (one when the grid is highly loaded and one when it is not) for two regions in Denmark (named DK1 and DK2 by the authors). The regions could import and export energy from three countries like Norway, Germany and Sweden.

The main function of the progra"s goal was as follows:

$$\min C_{DK1}^T * y_{DK1} + C_{DK2}^T * y_{DK2}$$

Where:

C_{DK1}^T, C_{DK2}^T – Vectors containing the bid (transposed) price of each supplier;

y_{DK1}, y_{DK2} – Vectors containing all variables evaluating the scheduled generation in the zones in each time unit (that is, the power generated by each market participant in each zone and their total demand)

The following restrictions have been set:

- Production from each generator must be less than or equal to the maximum available capacity for that unit
- The balance in both regions is checked in each unit of time, taking into account the maximum capacity of the transmission line;
- if the demand in a given hour is greater than the maximum production of each region, the power plants have been allowed to shed load

The revenue of each market participant is calculated as the product of the amount of energy delivered and the market clearing price.

The following results were obtained from the simulation:

- In the case of a highly congested transmission line day, the market price is more than four times higher than for an uncongested one and the total system cost is also significantly higher (because when the line is congested you have to source energy from more expensive suppliers);

- When RES are able to cover energy demand they are mainly used because they are cheaper and more distributed (transmission lines do not have to be overused)
- Renewables generate a lot of revenue for generators when they operate because they have low generation costs and are often chosen– according to the merit order principle
- Renewable units push more expensive coal units out of the market– renewable energy changes the market by lowering energy prices; unfortunately, expensive coal units are still the base units needed in the system;

1.5.4 "Agent-based Model for Spot and Balancing Electricity Markets"

The authors of the publication, Florian Kühnlenz and Pedro H. J. Nardelli, wanted to present an agent-based modeling of the electricity market in a simple and user-friendly way. The proposed model combines spot (long term and day-ahead) and balancing markets, clearing at a frequency of 1 minute (rather than hourly as in real life–- to model the balancing market more accurately), in order to represent the power grid as realistically as possible. As part of the test, they compared the results obtained from our simulation with data from Nord Pool.

In order to show the relationship between market participants as realistically as possible, it was decided to use an agent model (three agents were considered: producers, utilities and users). It describes how the three markets coexist, from contracts going back several years to real-time power purchases in the balancing market. In its basic form, the model cannot predict specific outcomes but only general behavior. The entire principle of the program is based on the Nord Pool market and its underlying price-matching algorithm, Euphemia.

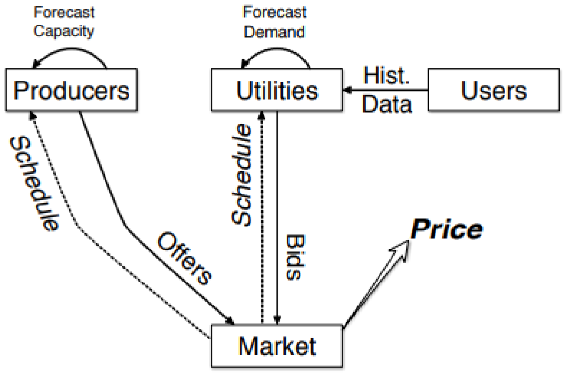


Fig. 2. Spot market period. First time step: Utilities forecast the demand of their users and submit bids accordingly; producers forecast production capacity and submit offers accordingly. Second time step: market matches bids and offers to create schedules and a public price.

Figure 1.7–- Diagram of the energy market model built in the simulation [10]

Each simulation day runs in three main stages: the previous day's market, the next day's market and the balancing market. Producers submit their bids and deliver power according to their forecasts. Companies have no price elasticity– their bids are always matched accordingly and all whose price is less than or equal to the clearing market price are accepted. Balance bids are also arranged in merit order and selected from the cheapest.

Disproportions between production and consumption are checked every 15 minutes. Depending on the disparity and the market situation (shortage or surplus of power), appropriate regulation bids are selected. Then the power plant whose bid was preempted is removed from the list so as not to accidentally expose it to rapid power changes.

To verify the results, they were compared with data from NordPool. Overall, the simulation gives results similar to the Nord Pool data, taking into account simplifications.

2 Aim and scope of the thesis

2.1 Aim of the Thesis

Energy markets and the question of how to combine them are already described in the literature. However, it is such a complex subject that, in my opinion, scientific publications alone are not enough to understand it well. My goal, therefore, is to study and describe the behavior of energy markets, their interpenetration and mutual influence on each other. Mainly, I will want to trace changes in the price of electricity depending on the behavior of energy market participants and the current geopolitical situation in the world. I will create three teaching tools (computer applications). They will allow which will allow me in this work and hopefully other students in the future to play the role of energy market participants, make economic decisions on their own and follow their consequences.

2.2 Research questions:

- How will the development of RES affect the price of energy?
- How can weather affect the price of energy (in general - e.g. "windy day", "not much sunshine day")?
- How can the failure of large generating units affect the price of energy?
- How does a sudden increase in fuel prices (e.g., like the increase in the price of gas after Ukraine's attack on Russia) affect the change in the price of energy ?
- How do the day-ahead market and the balancing market interact?
- How does the existence of the balancing market affect the country's energy security ?
- How does the composition of the energy mix affect the price of electricity ?
- How does the situation in the energy market (shortage, oversupply) affect the profits of its various participants (DSOs, generators), when which situation and to whom is most profitable?
- The impact of errors in demand forecasting on energy prices and profit of market participants

3 Methodology

The aim of my work is to study the effects of cooperation of energy markets (in particular the day-ahead and balancing markets) on energy prices. On the basis of several similar projects, the details of which I have provided above, I will create three applications that support teaching and allow me to simulate different situations on the markets. The first of the applications will allow you to freely select some cost and technological parameters of the power plant so as to freely maneuver the merit order principle. The second simulation will simply show the dependence of prices on the balancing market in the context of those set on the Day-Ahead Market. The last firmware will be the most extensive. Only basic functionalities will be introduced to it for the time being. It will be an optimization linear model simulating the Day-Ahead Market using the Pyomo library written in Python. The program will be an educational tool which, when used during classes, will allow students to play the role of participants in the energy market. I will use the agent modeling approach for this purpose.

3.1 Application 1 - "Merit Order Simulation"

The first of the scientific applications built smugly jets the simulation of energy pricing in the Merit Order system. The application allows selecting any energy generation technologies, determining the variable and fixed costs of production of each technology and their efficiency. In addition, it is possible to include in the simulation the amount of CO_2 prices depending on the emissivity of a given technology.

3.2 Description of tools:

I used the Python language to prepare the model. I programmed mainly in the PyCharm environment and Visual Studio Code. I used the following libriares:

- **NumPy** - for operations on arrays and arrays of data
- **Matplotlib** (together with **Matplotlib.widgets**) - drawing charts and adding interactivity to the chart, e.g. sliders, checkbuttons, buttons; creating an application interface;
- **Pandas** - operation on "dataframe" (large data tables in Python)
- **Tkinter** - to create a menu window for editing data in the application

3.2.1 Input Data

The data for the simulation covers one year of time from 01.06.2022 to 31.05.2023 inclusive. They were downloaded from the PSE website and will be compiled in the following chapters.

3.2.2 Technological Data

First, let's consider what's on each part of the screen. Figure 3.1 shows the application's start screen immediately after launching it. Under the following numbers are:

1 - editing CO_2 emission parameters

2 - setting the simulation to the starting conditions for Poland

3 - panel for switching on/off the technologies under consideration

4 - chart field

5 - information on simulation results

6 - sliders allowing to set installed power and prices of individual technologies

7 - numerical confirmation of values set on the sliders

8 - slider for setting energy demand

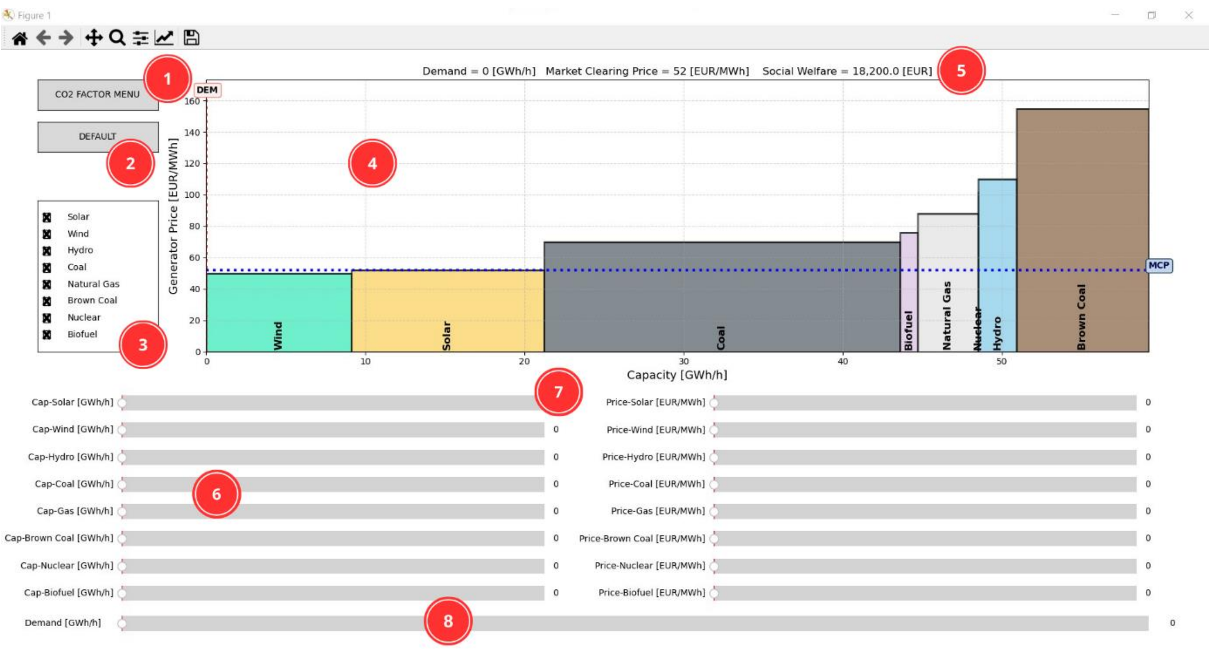


Figure 3.1 - Main menu Merit Order application (created at canva.com)

After clicking on button no. 1 ("DEFAULT"), the sliders and the whole simulation will change to the data from Table 4.7 and Table 4.9 presented in Chapter 4. For the time being, emissions are not taken into account and the coefficients are set to 0. The sliders can change respectively the installed power in technologies (width of bars on the graph) and the LCOE price for electricity (height of bars). To change their value, just click and move the white balls at the ends of the colored bars and the value on the graph will change on its own. The currently set energy demand is shown by the red line with the "DEM" marker. The horizontal blue line with the marker "MCP" sets at the height of the marginal price of the most expensive technology involved in energy production - the "market clearing price".

In the technology box on the left side of the screen, you can turn individual technologies on and off by clicking on the boxes next to them. As can be seen in Figure 3.2, in the base case the power plant is turned off because Poland does not yet have one in 2023.

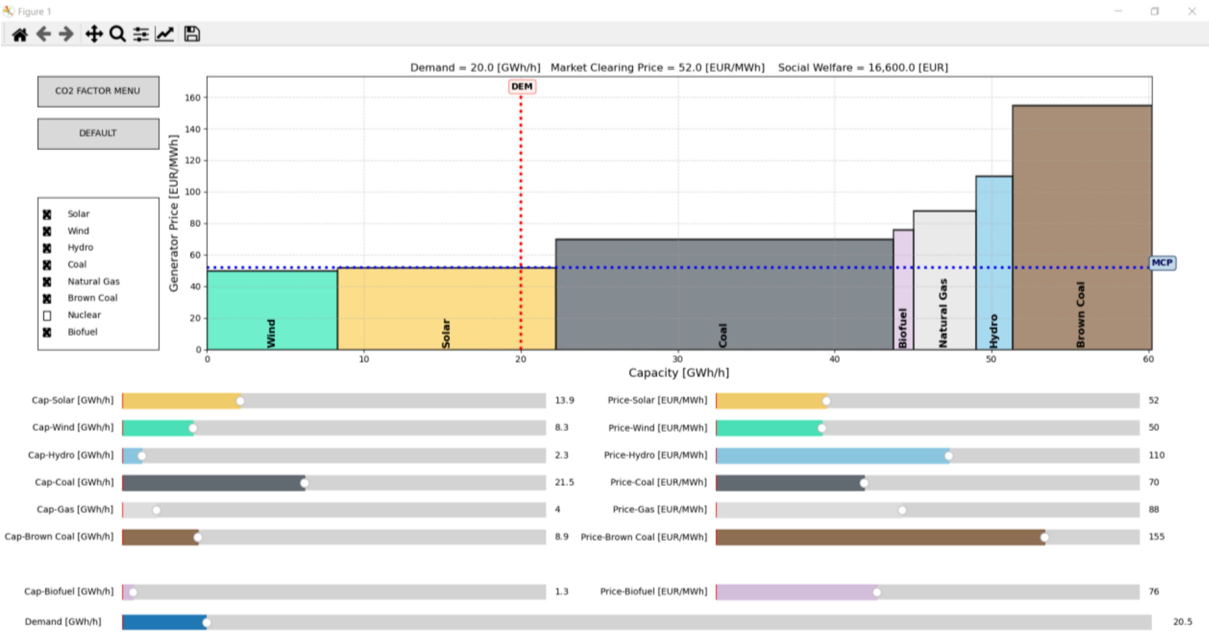


Figure 3.2 - Main menu of application afer pressing button "Default"

If we would like to set the CO_2 emission parameters, we need to click on the "CO_2 factor menu" button and a window will appear as in Figure 3.3. At the start, in order to have the emission counting disabled, everywhere where there is an emission factor is entered 0.

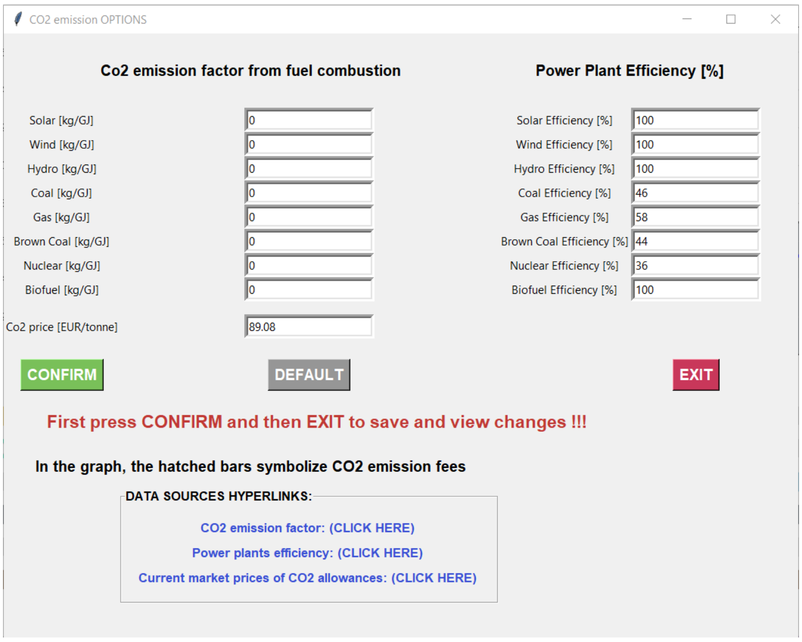


Figure 3.3 - CO_2 emission factor menu – zero emission factor case

If you want to use the default emission data entered in the program, click the "DEFAULT" button and then confirm with the green "CONFIRM" button. Then the parameters on the screen should look like in Figure 3.4. Finally, click the red "EXIT" button to see the changes. If we would like to use other coefficients or set other power plant efficiencies there is no problem with this, enter them in the appropriate boxes and then follow the previous instructions, that is, click the "CONFIRM" button and then "EXIT". At the bottom of the screen in a box, in addition, there are hyperlinks which, when clicked, will open a page with the current data used in the simulation.

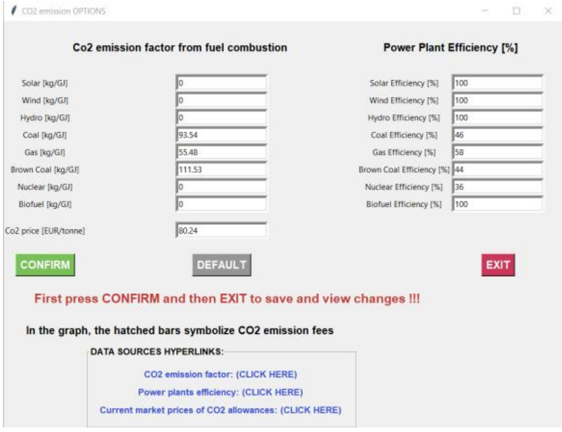


Figure 3.4 - CO_2 emission factor menu – default emission factors case

After accepting the changes, the chart area should look like Figure 3.5. The gray lines symbolize the CO_2 costs that you will have to pay in addition to the usual energy production costs. In addition, above the graph there is information about the currently set energy demand - "Demand", energy price - "Market Clearing Price" and producers' excess profits - "social welfare".

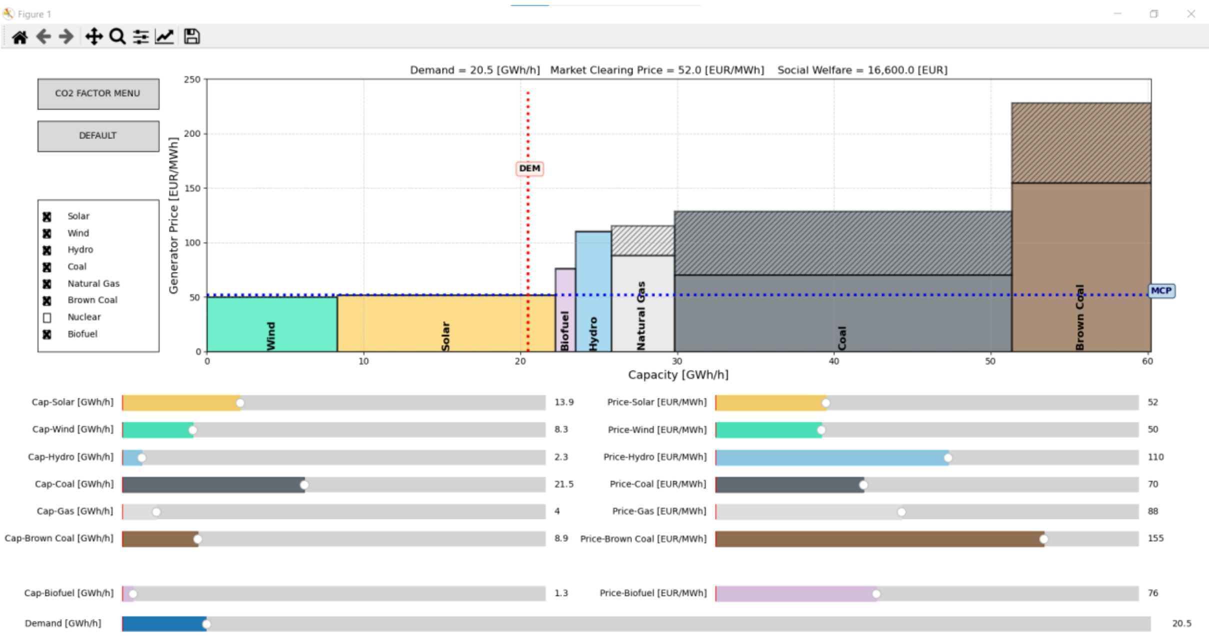


Figure 3.5 - Main menu of application - after including CO_2 emission costs

3.3 Application 2 - "Balancing Market Simulation”

In Poland we can distinguish several types of energy markets, depending on the required date of delivery. The energy price set on the Day-Ahead or Intraday Market is rarely the final price. In the 24 hours between the conclusion of a contract on the Polish Power Exchange, the energy demand profile can change completely. Depending on whether there is too much ("down-regulation") or too little ("up-regulation") energy on the market, its final price is higher or lower than previously set.

3.3.1 Description of tools:

As in subsection 3.5.1, in this project I used the Python language and two of its libraries Numpy and Matplotlib.

3.3.2 Input Data

In preparing the study, I mainly relied on the following source [14].

3.3.3 Technological Data

After turning on the program, our eyes will see the startup screen as in Figure 3.6. The blue line symbolizes the generators' bids for energy supply.

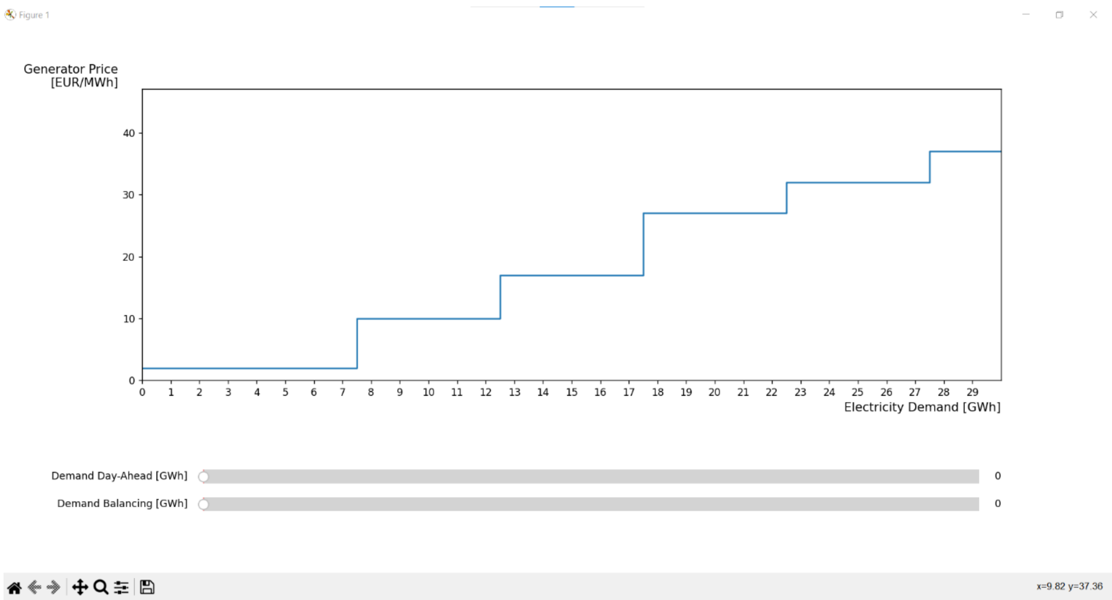


Figure 3.6 - Start screen of the application that simulates the price change on the balancing market

In the second step, you need to set the energy demand for the Day-Ahead Market and the Balancing Market. This is done using the sliders at the bottom of the screen.

A picture similar to the one in Figure 3.7 will appear before our eyes. The red box symbolizes the difference between the energy demand in the Day-Ahead Market and the actual demand that must be met through the Balancing Market. The red vertical line indicates the demand in the Day-Ahead Market and the blue line in the Balancing Market. The black horizontal line indicates the price that has been set in the Day-Ahead Market and the yellow one that will be set in the Balancing Market.

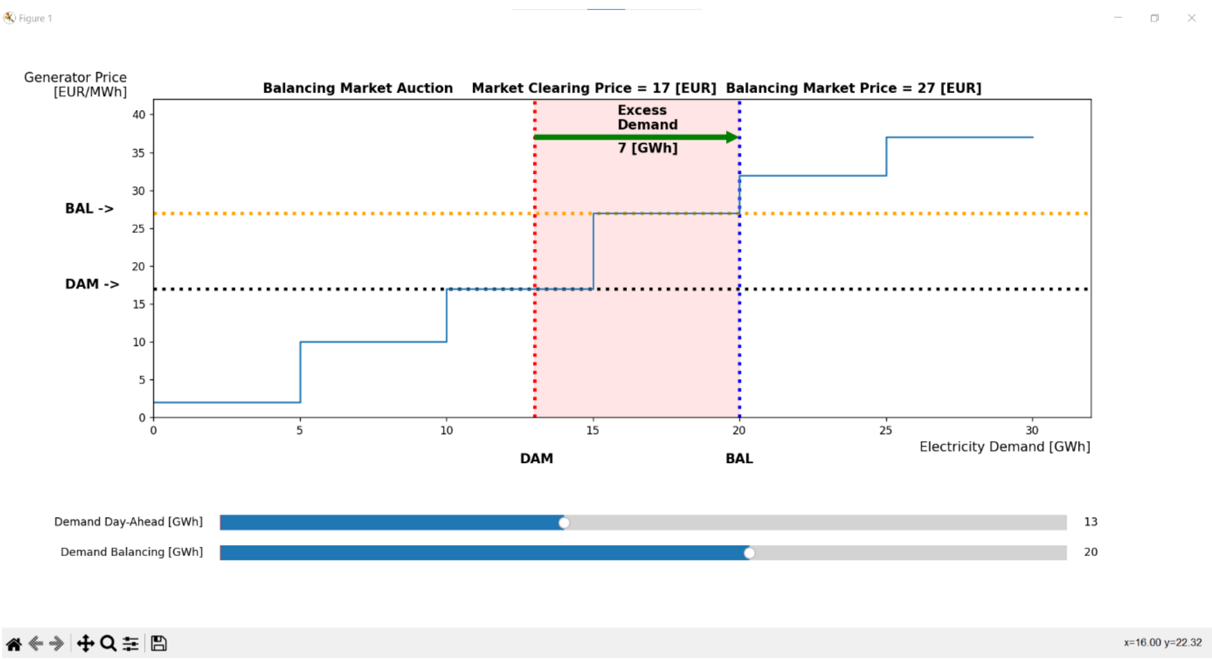


Figure 3.7 - Exemplary screen of the application after set random data

3.4 Application 3 - "Simulation of the Day-Ahead Market."

3.4.1 Description of tools:

In writing this application, I used the same Python language libraries as in subsections 3.1.1, 3.2.1 and additionally:

- **Pygame** + **socket** - to create local game server
- **Pyomo** – for optimalization
- **Pyplot** – for draw dynamic charts
- **OpenPyXl** – to transfer data between excel and the application (at this point, excel acts as the application's database)
- **Screeninfo** – blibiquette used to retrieve data on monitor size (so that the application scales automatically to different display sizes)
- **Time** – to control the timing of the application (used to avoid collisions between loading application elements)
- **Datetime** – module to convert data from Excel to date format

Object-oriented programming was also used here, i.e. the classes on which the dynamically opening windows were based.

The entire application is based on a number of Python modules that are responsible for its various functions. The code follows good programming practices.

3.4.2 Input Data

In preparing the study, I mainly relied on the following source [15].

3.4.3 Technological Data

As part of my master's thesis, I also programmed a preliminary version of an interactive game for students, simulating the Day-Ahead Market. In the next phases of the application's development, it is planned to implement a turn-based game and add a balancing market. Finally, the game is to be made available to students in WLAN mode, so that even a dozen people can play it during one class.

In the game, students can take on one of three roles: controllable power plants, non-controllable power plants and those who buy energy on the market. Based on a smart draw at the start of the game, each player is assigned initial limiting values such as the unit's installed capacity or the demand it must fill. Each conventional power plant in is a real unit operating in Poland and available in 2022. The data was downloaded from the PSE website. [16]

Each of them makes an offer to buy or sell. Then an offer stack is created according to the Merit Order system. Then, at the end, a table is displayed with the results is earned the most.

At this point, it is possible to select any number of players, and the whole optimization works, the purpose of which is to maximize social welfare and selects the price of energy.

Thanks to my application, students will be able to try their hand at managing the energy market, shaping its price and maximizing profit.

Checking the correctness of calculating social welfare for random data

In the simulation, the main goal is to maximize social welfare, so it is important to me that it is calculated correctly.

The program counting social welfare was written according to the same algorithm but using two programming languages python and its library Pyomo and GAMSA. In both cases the same solver CPLEX was used. Both programs are of the Linear Programming type.

The same equations (7a-d) are implemented in both programs. Equation (7a) is called the "objective function" and is designed to maximize social welfare. Equations (7b-d) are "constrains" and are designed to limit the number of solutions to the result. In this case, we assume that the sum of energy sold must equal the energy demand. The last two equations say that the consumer cannot buy a negative amount of energy or more than he needs, and the seller cannot sell more than his power plant produces.

$$Max. \sum_{i,j=0}^{n} \left(P_{D\,i} * \lambda_{D\,i} - P_{G\,j} * \lambda_{G\,j} \right) \quad (7a)$$

$$s.t.\ \sum_{i=0}^{n} P_{D_i} = \sum_{i=0}^{n} P_{G_j} \quad (7b)$$

$$0 \leq P_{G\,j} \leq P_{G_{\mathrm{jmax}}} \quad (7c)$$

$$0 \leq P_{D\,i} \leq P_{D_{\mathrm{imax}}} \quad (7d)$$

Where:

$P_{D\,i}$ – the amount of energy that distribution system operators buy [MWh]

$\lambda_{D\,i}$ – the price that the distribution system operators propose for energy [EUR/MWh]

$P_{G\,j}$ – the amount of energy the generators sell [MWh]

$\lambda_{G\,j}$ - the price the generator proposes for energy [EUR/MWh]

$P_{G_{\mathrm{jmax}}}$ – maximum installed power of the generator [MWh]

$P_{D_{\mathrm{imax}}}$ – maximum energy demand distribution system operators [MWh]

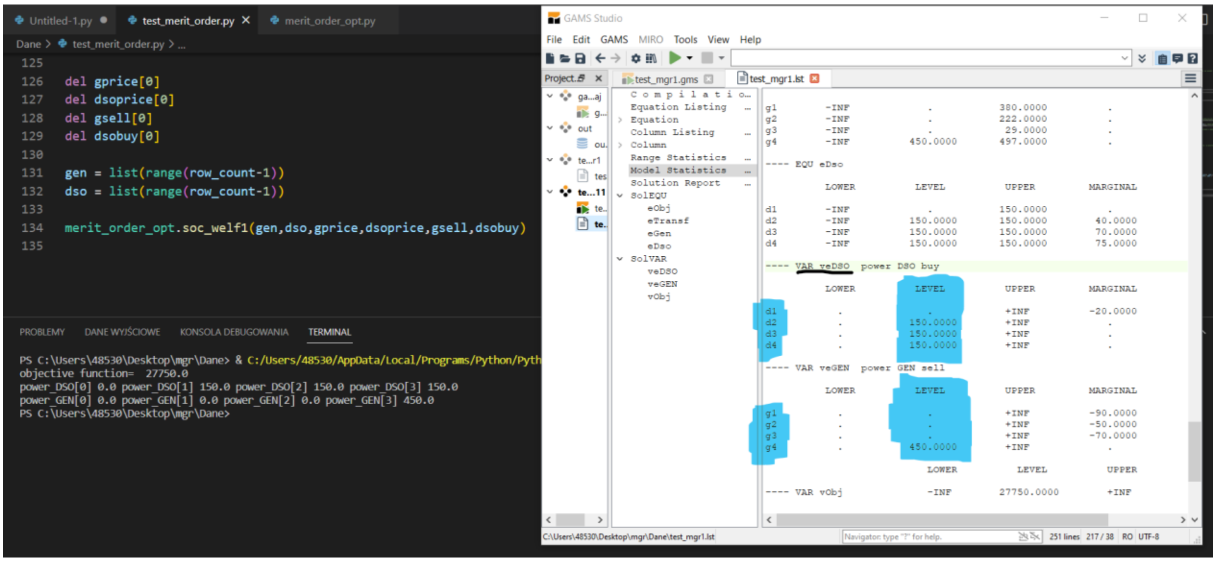


Figure 3.8 - Comparison of results of programs counting social welfare day ahead market (own elaboration)

As Figure 3.8 shows, the algorithm gave the same results in both programs, so it is very likely that they are correct. The code of the programs can be found in Appendix C to the following thesis. Sample data used in the simulation are provided in Table 3.1 and Table 3.2.

Table 3.1 - Random test data for day ahead market simulation - generators

nb	plant_name	max_prod_MWh	sell_MWh	price_EUR_MWh
1	Bełchatów B04	Brown_coal	380	200
2	Dolna Odra B6	Hard_coal	222	160
3	Dychów H2	Hydro	29	180
4	EC Żerań 2 B20	Natural_gas	497	110

Source: own elaboration

Table 3.2 Random test data for day ahead market simulation - consumers

nb	demand_MWh	buy_MWh	price_EUR_MWh
1	221,42	150	90
2	221,42	150	150
3	221,42	150	180
4	221,42	150	185

Source: own elaboration

In addition, a Merit order chart (Figure 3.9) was generated using Python to see if the results agreed with my engineering knowledge.

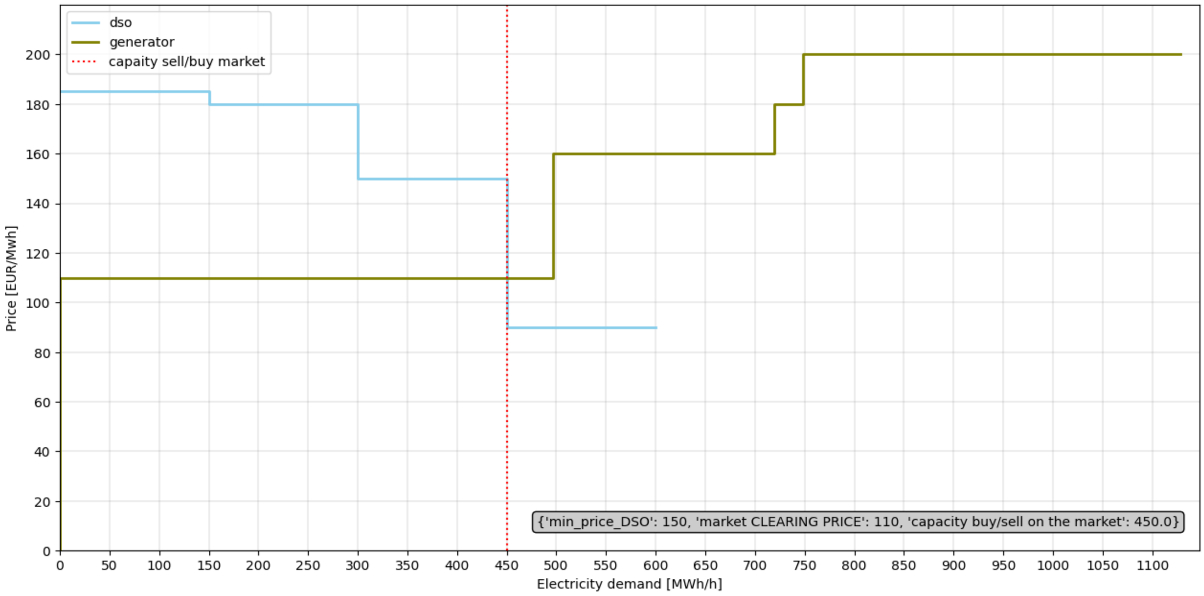


Figure 3.9 - Merit Order chart showing the results of the test presented in Figure 3.8 (own elaboration)

As you can see in Figure 3.9, the total energy demand was 450 [MWh]. Everything works according to the Merit Order principle. All the buyers to the left of the red line on the chart have been contracted. So the energy will go to the 3 buyers who put up the most expensive bids (numbered 2,3,4). They bought energy from only one, the cheapest supplier with number 4 (EC Zeran 2 B20). This maximized social welfare (Equation 7a). The rest of the suppliers and buyers will have to procure energy in the second round of the Day-Ahead Market or directly in the balancing market. The situation shown in the graph agrees with the calculations made on the programs (Figure 3.8). Also indicated there are the same units that have been contracted.

Instructions on how the game works

First, before launching the game, you need to fire up the server file and specify how many players our game will have and what type they are (Figure 3.12). Then you can already fire up the file with the main menu (Figure 3.11). The main menu in the future will offer a direct transition to the two previously discussed applications. To enter the game, click the "JOIN THE MULTIPLAYER GAME" button. A player selection window will appear to our eyes (Figure 3.10).

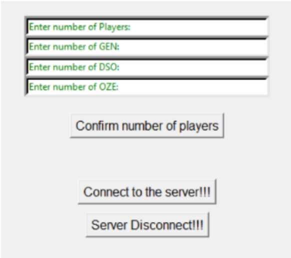


Figure 3.12 - Server file run

Figure 3.11 - Main menu GUI

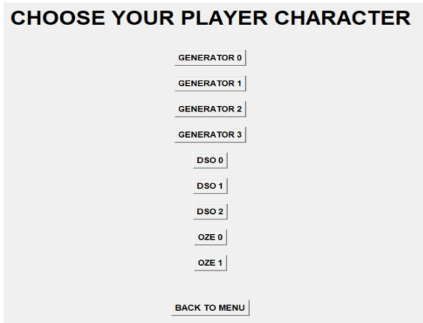


Figure 3.10 - Player selection menu

We can choose from 3 types of agents: generator, RES generator and DSO. Each participant, in turn, selects one character AND enters in a special box how much energy he wants to sell/buy AND at what price (Figure 3.13). On the left side we have all the information about the parameters of our unit. These are intended to make the game more interesting and realistic.

Each subsequent player will have fewer units to choose from and those already selected will turn red (Figure 3.13). After clicking the "CONFIRM" button (Figure 3.15), the chart loading window will appear on the screen (Figure 3.14).

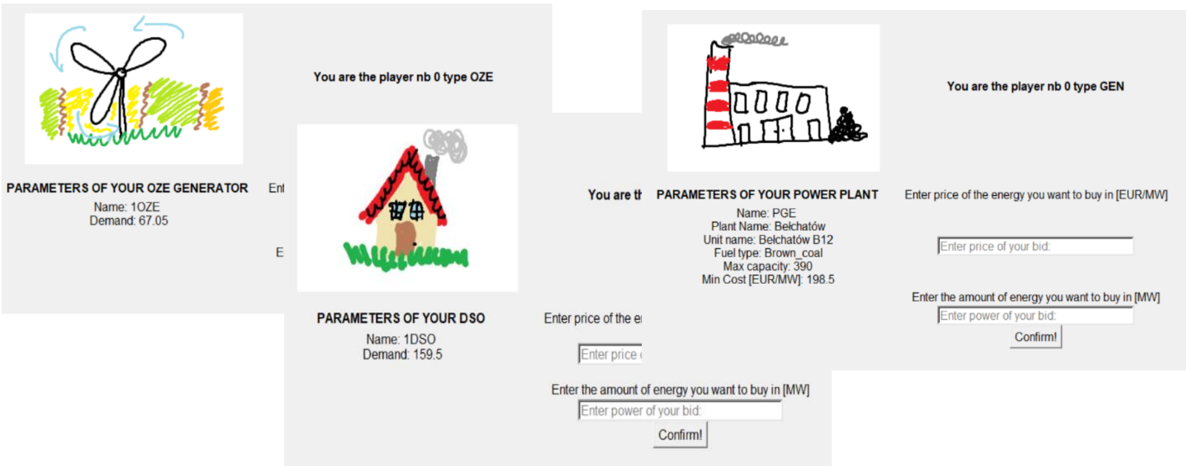
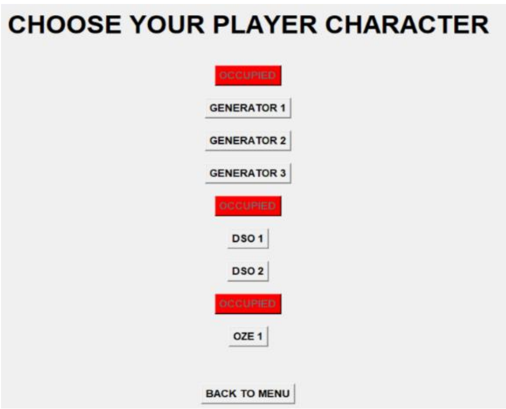


Figure 3.15 - Windows of different types of agents players



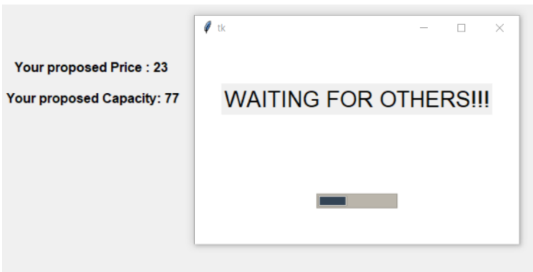


Figure 3.14 - Window of waiting for others after bidding

Figure 3.13 - Player selection window after submitting part of bids

All the data entered are accumulated in an excel sheet in a special table. So at the end of the game you can see who sold/buy how much energy and earned the most (Figure 3.16).

	A	B	C	D	E	F	G	H
1	plr_name	power buy/sell MWh	B-buy, S-sell	proposed_price_EUR_MWh	MCP_EUR	Income_EUR/outcome	max_cap/demand_MWh	left_MWh
2	GEN0	0	S	200,00	100,00	0,00	316,85	316,85
3	GEN1	77	S	23,00	100,00	1771,00	390,20	313,20
4	GEN2	183	S	100,00	100,00	18300,00	156,00	-27,00
5	DSO0	0	B	50,00	100,00	0,00	383,00	383,00
6	DSO1	0	B	100,00	100,00	0,00	150,00	150,00
7	DSO2	150	B	185,00	100,00	27750,00	150,00	0,00
8	DSO3	110	B	160,00	100,00	17600,00	150,00	40,00

Figure 3.16 - Game summary in excel sheet

4 Results

4.1 Analysis of system data of energy demand, fuel prices and generation from RES power plants

4.1.1 LCOE

Levelized cost of energy (LCOE) - is an indicator of the profitability of energy production from a given power plant; it is the average cost of producing a unit of energy by a given power plant during its entire life cycle; it is calculated as a ratio of the total cost of investment (CAPEX) and operation (OPEX) of the period to the total energy production during the life of the power plant; sometimes CO_2 emission fees are omitted from the calculation and sometimes are added to operating expenses; however, it is becoming increasingly common for scientific papers to include such a component in their calculations; thanks to this coefficient, we can compare different energy sources in terms of cost-effectiveness [17];

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \left[\frac{EUR}{MWh}\right] \qquad (1)$$

Where: [18]

I_t - Investment and expenditures for the year (t)

M_t - Operational and maintenance expenditures for the year (t)

E_t - Electricity production for the year (t)

r - Discount rate that could be earned in alternative investments

n - Lifetime of the system

Table 4.1 - LCOE costs for different areas of the world, excluding CO_2 costs (pink - average costs, recalculated from USD to EUR at 2019 average exchange rate, green and blue recalculated from USD to EUR at 2021 average exchange rate [Appendix A: (a)]);

Source ->	[17]	[19]	[20]	[21]
Region ->	EU	GLOBAL	GERMANY	EUROPE
Year	2022	2023	2021	2021/22
Technology	**Price [EUR/MWh]**			
wind on-shore	50	40	60	36
pv	67	42	70	52
hard coal		70	129	
lignite			155	
CCGT		87	104	88
nuclear		214		
biomass -solid			113	
biogas			129	
hydro >=10 MW				11
biofuel (overall)				76

Source: own elaboration based on [17], [19]–[21]

In order to select parameters in my simulation that are as close as possible to the current situation on the fuel and energy market, I juxtaposed several scientific studies. The data comes from a maximum of 2 years back and I've compiled everything in Table 4.1. We can thus compare prices in different parts of the world, although I care most about Europe because it is geographically and politically where Poland belongs. We can see that prices in Europe are higher than global prices and that they increase over the years. In my opinion, the increase in prices of such power plants as PV or offshore wind is mainly due to the increase in popularity of these types of installations which does not go hand in hand with major technological advances. In addition, the passing of covid 19 has left large voids in the warehouses of suppliers of key building blocks such as silicon and electronic parts. I will rely on this data when deciding on the final fuel price in my simulation. The values in the table seem quite reasonable, however, there are still a few issues to be sure. First of all, I was concerned about the high price for nuclear fuel, which was not studied for Europe in the publications mentioned above. So I tried to find studies on the price of this Fuel in Europe. I have compiled them in Table 4.2. The original document gave prices for these fuels for 3 different possible discount rates.

Table 4.2 - Projected nuclear LCOE costs for plants built 2020-2025, $/MWh

Country	At 3% discount rate	At 7% discount rate	At 10% discount rate

France	45,3	71,1	96,9
Russia	27,40	42	56,6
Slovakia	57,6	101,8	146

Source: own elaboration based on [22]

I decided in my calculations to assume the middle value of the discount rate from Table 4.2 (7%) and to assume the price value for Slovakia (due to the fact that it neighbors Poland and is at a similar level of development - they have the most similar GDP "per capita" [23]). This article justifies why I decided to compare the level of development of countries using the GDP per capita index [24].

4.1.2 Prices of natural gas, coal and other fuels in Poland and around the world

Natural Gas Prices

The price of energy closely depends on the prices of fuel commodities. In the next few paragraphs, I would like to consider the price changes of two key fuels (coal and natural gas) in the context of their subsequent impact on energy prices.

Table 4.3 - Annual Industrial Gas Prices (EUR/MWh) in the EU in 2022 - excluding taxes (currency converted as semiannual average from data [Appendix A: (b)])

Price of Natural Gas in 2022 [EUR/MWh] - excl taxes				
Period	**Type of consumers**	**Poland**	**EU 27 +UK median**	**Germany**
Jan-June 2022	Small	64,14	67,06	44,78
Jul-Dec 2022	Small	69,51	104,79	55,03
Jan-June 2022	Medium	74,00	67,81	44,54
Jul-Dec 2022	Medium	95,34	99,59	52,02
Jan-June 2022	Large	76,51	65,36	48,70
Jul-Dec 2022	Large	93,10	93,10	62,80

Source: own elaboration based on [25]

The data source of Table 4.3 states that the size of energy consumers is understood in terms of the categories shown in Table 4.4

Table 4.4 - The sizebands of consumer type for data in Table 4.3

Industrial Gas	Eurostat size band	Annual consumption (MWh)
Small	Band I2	278 - 2,777
Medium	Band I3	2,778 - 27,777
Large	Band I4	27,778 - 277,777

Source:based on [25]

Analyzing the data in Tab.5, we see that in the last year, the more gas Europeans consumed annually, the more expensive it became. This has to do with the collapse of the gas market in Europe in early 2022, due to Russia's invasion of Ukraine. The cheapest gas was had by Germans who began to shut down their nuclear power plants and switch to this fuel, importing it from Russia, also after its invasion of Ukraine. They also have large stocks of the resource. In the first half of 2022, prices in Poland were lower than in Europe for small customers, but much higher for large ones. In the second half of the year, the statistics reversed a bit and prices in Poland were no longer higher than the European average (especially for medium-sized buyers. Why this happened is represented by the chart below (Figure 4.1), which is based on the same data, but in an expanded version. I deliberately compare Poland to Germany because they are neighbors and yet have different gas policies. The EU average price shows the state of the entire continent.

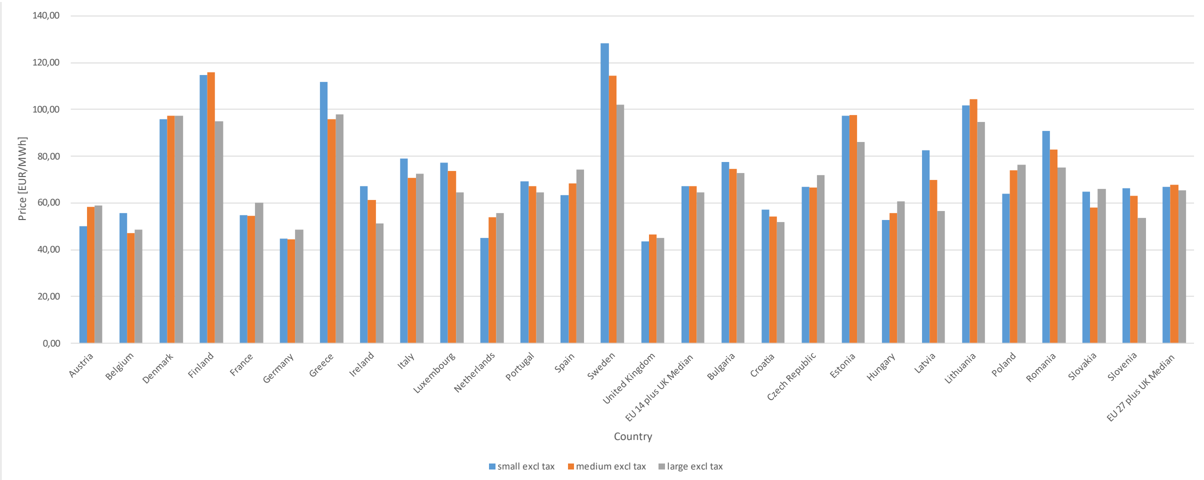


Figure 4.1 - Graphical representation of the data in Tab.5 for several EU countries "Annual Industrial Gas Prices (EUR/MWh) in the EU in 2022" - Jan-June 2022 [25]

The graph in Figure 4.11 shows us the magnitude of the problem that emerged in 2022 after Europe was virtually cut off from Russian gas. The cheapest gas was Britain which has a lot of nuclear reactors. This is joined by Germany, which still imported a lot of gas from Russia, and the Netherlands with an energy mix based largely on renewables. Having a large number of reactors, however, does not guarantee the lowest electricity prices, as can be seen from the posts for France, Spain or Slovakia. The highest prices were in the Scandinavian countries (Finland and Sweden) and Greece, which is recovering from the crisis, had the highest prices and they bore the European average.

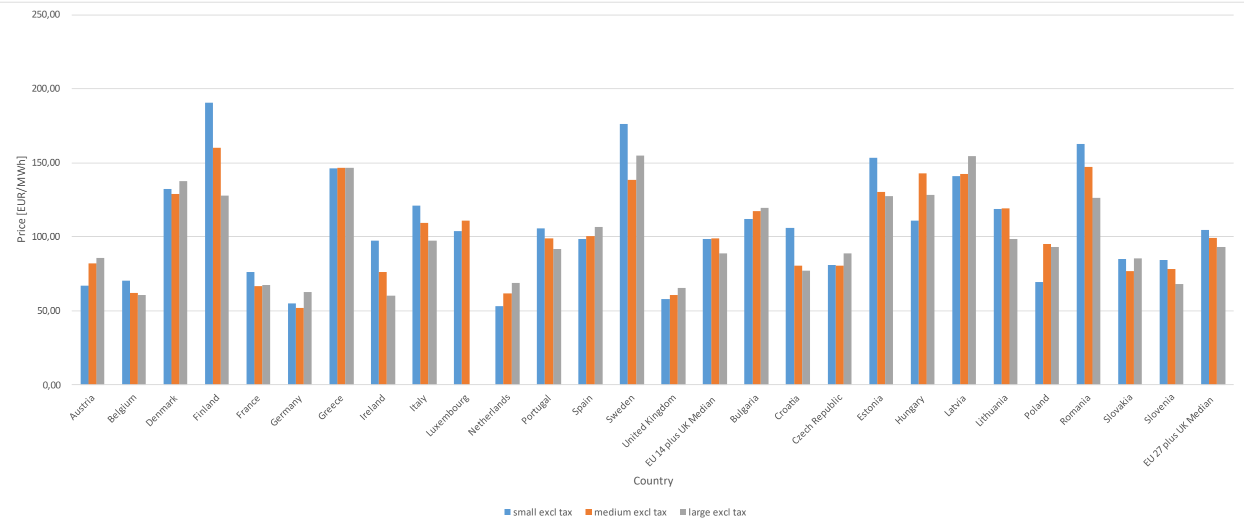


Figure 4.2 - Graphical representation of the data in Tab.5 for several EU countries "Annual Industrial Gas Prices (EUR/MWh) in the EU in 2022" - June-Dec 2022 [25]

In the second half of 2022 (Figure 4.2), gas prices rose virtually across the European Union, with the continental average increasing by as much as 56% for small customers, 47% for medium customers and 42% for large customers. As we can see in Figure 4.2, prices in Sweden and Finland continued to be the highest and at times exceeded those for the cheapest Netherlands by as much as three times.

Table 4.5 - Quarterly average prices of the most popular fuels in Europe and the United States in [USD/fuel unit]

Fuel type	Q3 2021	Q4 2021	Q1 2022	Q2 2022	Q3 2022	Q4 2022	Q1 2023	Q2 2023	Unit
European TTF Natural Gas	16,9	31,4	31,5	32,0	60,5	36,9	16,8	11,3	USD/MM Btu
Uranium U308	35,7	45,6	49,1	53,6	49,5	50,1	50,4	54,3	USD/lb

Brent Crude Oil	73,3	79,7	98	112,1	97,7	88,6	82,2	77,9	USD/bbl
Thermal coal	165,7	183,5	266,7	364,9	417,5	379,8	255,4	161,3	USD/mt
U.S. Henry Hub Natural Gas	4,3	4,82	4,5	7,5	7,9	6,1	2,8	2,3	USD/MM Btu

Source: own elaboration based on [26]

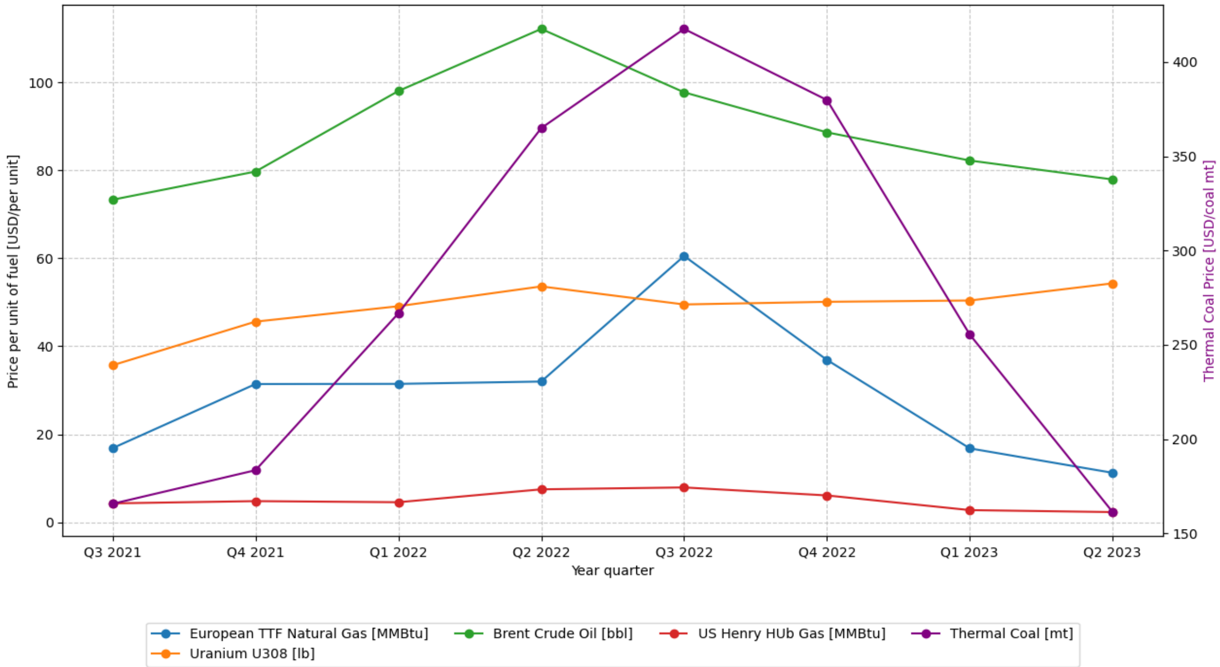


Figure 4.3 - Graphical representation of the data in Table 4.2 "Quarterly average prices of the most popular fuels in Europe and the United States in [USD/fuel unit]" [26]

In the chart in Figure 4.3, we can see that now (Q2 2023) virtually all prices for key fuels have returned to the levels of two years ago (exact quantitative data are shown in Table 4.5). Later, we will relate these changes to changes in energy prices over time. From this chart, we can see that Fuel prices began to climb in early 2022. This was around the time of Russia's invasion of Ukraine. Russia was one of the largest exporters of gas and coal in the world before the war [27], [28]. Ukraine, on the other hand, allocated one unit of the Dobrotwor power plant to produce energy for the Polish system.[29] After being almost completely cut off from Russia's supply of raw materials, countries had to look for another fuel substitute. Many of them have started projects to build nuclear power plants but it is known that the construction itself takes at least several years. Fossil fuels and other alternatives thus had to become a substitute for gas. This can also be seen in the graph. Coal and oil prices have jumped dramatically. The price of nuclear fuel is at a virtually constant level, its slight increase may be due to worldwide inflation. The aforementioned graph also very well illustrates the comparison between gas prices in the United States and the EU. The war has had little effect on prices in the US, however, on Europe significantly. I have not converted the prices here into Euros and fuel units into equal ones. I did this on purpose because I did not care about exact amount data but only to show the characteristics of fuel price changes over time.

Based on the data in Table 4.3 Table 4.1, for the purposes of my simulation I will assume that the price of natural gas per MWh will be €90.

Hard coal prices

Poland is following global trends and is moving away from coal-fired power generation more and more each year, leaning toward less carbon-intensive sources. As shown in Figure 4.4, coal mining in Poland has declined by almost 50% over the past 15 years. This is crucial in terms of the country's energy prices (since, as Table 4.7 will show later in the paper, coal-fired power plants still supply Poland with almost 40% of its energy).

To some extent, Poland's problem is its dependence on this raw material, the combustion of which emits significant amounts of carbon dioxide. As is well known, the higher the emissions, the higher the cost of CO_2 allowances which are getting more expensive every year (the graph of changes will be presented later in the paper in Figure 4.9).

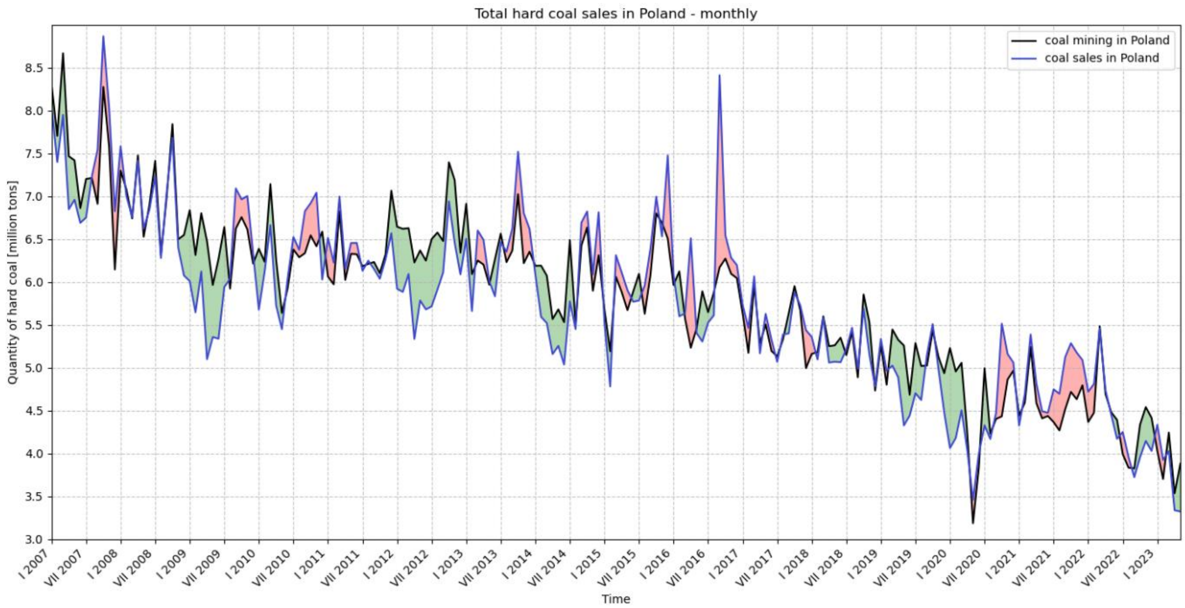


Figure 4.4 - Total hard coal sales and mining in Poland (Data source: Polish Coal Market (ARE S.A))

On the same graph we can also see that Poland is also mining less and less coal every year. The green color indicates the difference between coal extraction in Poland and coal consumption - when more is extracted than consumed. The red color indicates the same difference, but when extraction is less than consumption. Thus, it can be concluded that Poland is not only reducing coal consumption, but also coal mining, and in recent years has imported more coal than it obtained itself.

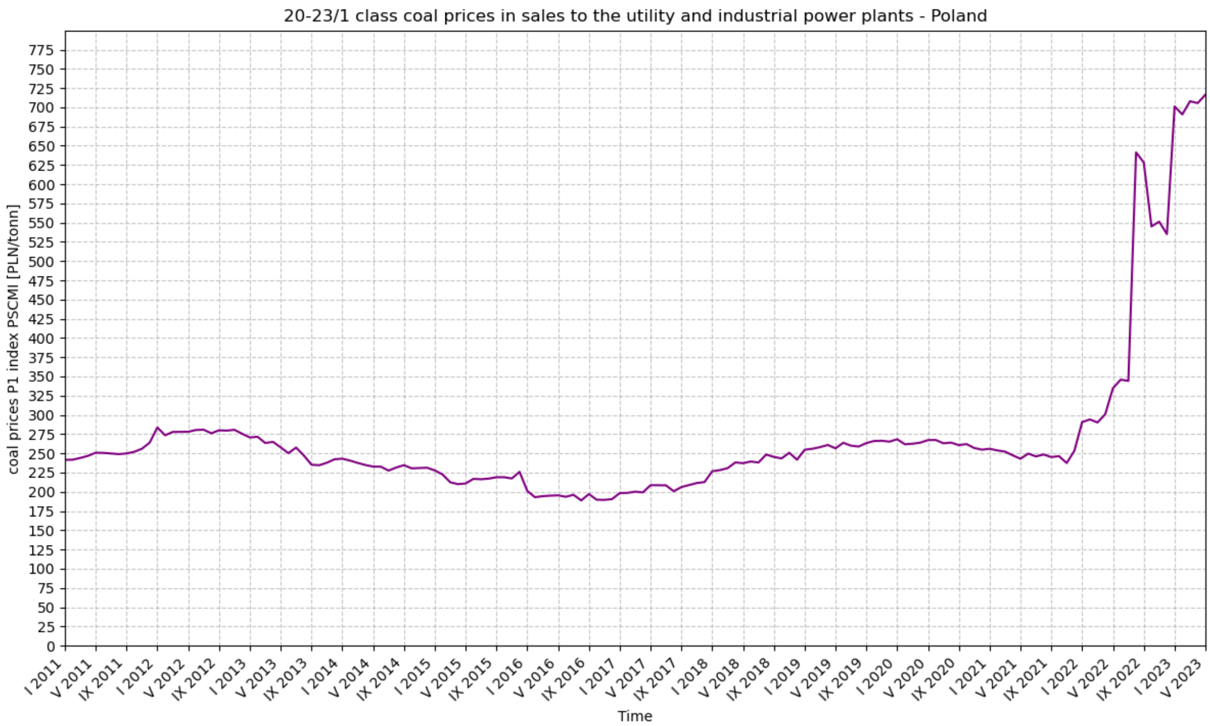


Figure 4.5 - 20-23/1 class coal prices in sales to the utility and industrial power plants - Poland [26,28]

Energy prices are influenced not only by the price of CO_2 emission allowances, but also by the price of fuel. The graph in Figure 4.5 shows the trend of changes in the price of hard coal in Poland. The prices in the chart are given in monthly resolution and are calculated according to the PSCMI1 index. This index reflects the price level of 20-23/1 grade fine coal in sales to the commercial and industrial power industry [28], [30].

Although the PSCMI index does not fully reflect the total final price of coal, it does give some idea of the dynamics of these changes. In the aforementioned Figure 4.5, we can see that for about a decade (between 2011-2021, until the beginning of 2022), the price of coal has fluctuated but never as dynamically as it has since the beginning of 2022. So far, the highest coal price was recorded in January 2012 (and it was PLN 283.61/ton) and the lowest in August 2016 (PLN 188.78/ton). In 2022, however, an unexpected thing happened. Coal prices jumped like never before after Russia invaded Ukraine. Poles cut off from Russian gas had to bail out with coal (we can see this as a big peak in coal demand in the first half of 2022 when people started to stockpile for fear of running out of fuel for the winter. The decline in sales of this commodity in the second half of 2022 in my opinion is the result not of less demand but of a reduced supply of coal which had to be rationed to citizens. In Poland it is the so-called "coal crisis". A law was introduced according to which municipalities bought coal from importers and for a maximum of 2,000 [PLN/tonn] were to sell it to eligible citizens. The limit was 3 tons of fuel per household, including 1.5 tons by the end of 2022 and another 1.5 tons in the first half of 2023 [31].

I suspect that the drop in coal prices in the winter of 2022 is due to the aforementioned laws and subsidies to citizens from the government because in the first half of 2023 coal prices jumped to their previous high and have continued to do so until today.

In this case (analyzing the graphs in Figure 4.4 and Figure 4.5 together), we see that the graph of low sales of the commodity does not necessarily mean low demand for it. Rather, a high commodity price and low sales suggest a high supply of a commodity that the market at any given time cannot saturate sufficiently. The other side of the coin is the more than 70% share of coal-fired power plants in the generation of coal-fired power plants in Poland in 2022. This topic will be developed in subsequent chapters while already at this point in the publication I would like to point out this fact.

CO_2 emissions

In the past year, Poland has made huge strides in reducing CO_2 emissions. Due to the fact that at the time of creating this publication it is difficult to find exact data for 2022 I will be using ready-made graphs of specialists in this analysis [32].

As can be seen in Figure 4.6, Poland had the largest overall decrease in CO_2 emissions in the EU last year. According to sources, we produced 184.15 million tons of verified emissions in 2022, which is almost 8 million tons less CO_2 equivalent than in 2021. Emissions declined in 7 countries but the EU as a whole managed to reduce emissions by 25 million tons of CO_2 [32].

Experts predict that the decrease in Poland's CO_2 emissions in 2022 occurred due to rising energy prices and high coal and gas prices (Table 4.5). When energy is expensive then people try to save it more, and invest more in renewable energy installations such as PV, micro wind turbines or heat pumps (in 2022 Poland had the third largest installed capacity in photovoltaics in the EU last year, and also has the fastest growing market for heat pumps) [32]. Poland has the second-highest electricity production emission factor in the EU after Estonia, meaning it ranks high in terms of ETS emissions, which account for about half of all national emissions.

Despite the good performance overall in terms of CO_2 emission reductions, in terms

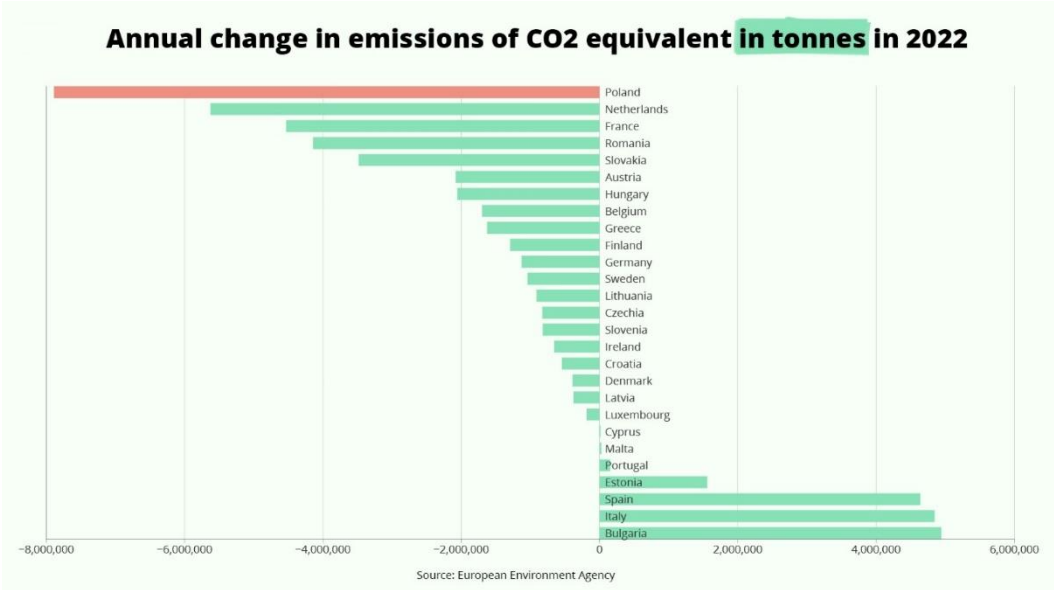


Figure 4.6 - Annual change in emissions of CO_2 equivalent [tonns] in 2022 - EU [37]

of percentage change ratio, Poland was only the 16th largest in the EU (Figure 4.7). The percentage change in emissions relative to 2021 was recorded in Latvia , Slovakia and Lithuania. Despite the large nominal decline, Poland's emissions are still nearly 8% above the lowest level recorded in 2020, when pandemic-induced lockdowns forced many companies to halt operations. Poland was recently named the EU's least green country in an index that takes into account the state of the environment, its impact on quality of life, and the efforts of politicians, businesses and citizens to address climate issues [32]. However, continued development and investment in renewable energy and nuclear power give hope for much higher rankings in future years.

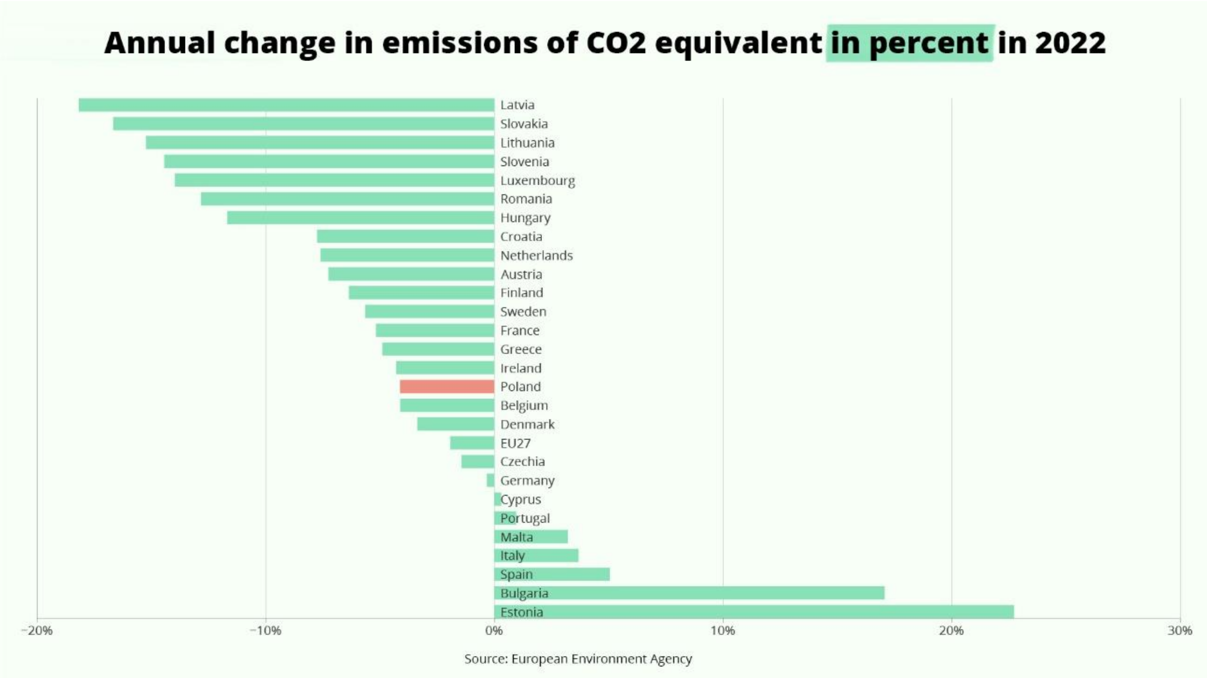


Figure 4.7 - Annual change in emissions of CO_2 equivalent in percent in Poland in 2022 [37]

Another CO_2 indicator that shows emissions only in a slightly different perspective is "per capita" emissions - that is, calculated per citizen of a country. This is a good indicator because it excludes the effect of the area of the country and population on emissions.

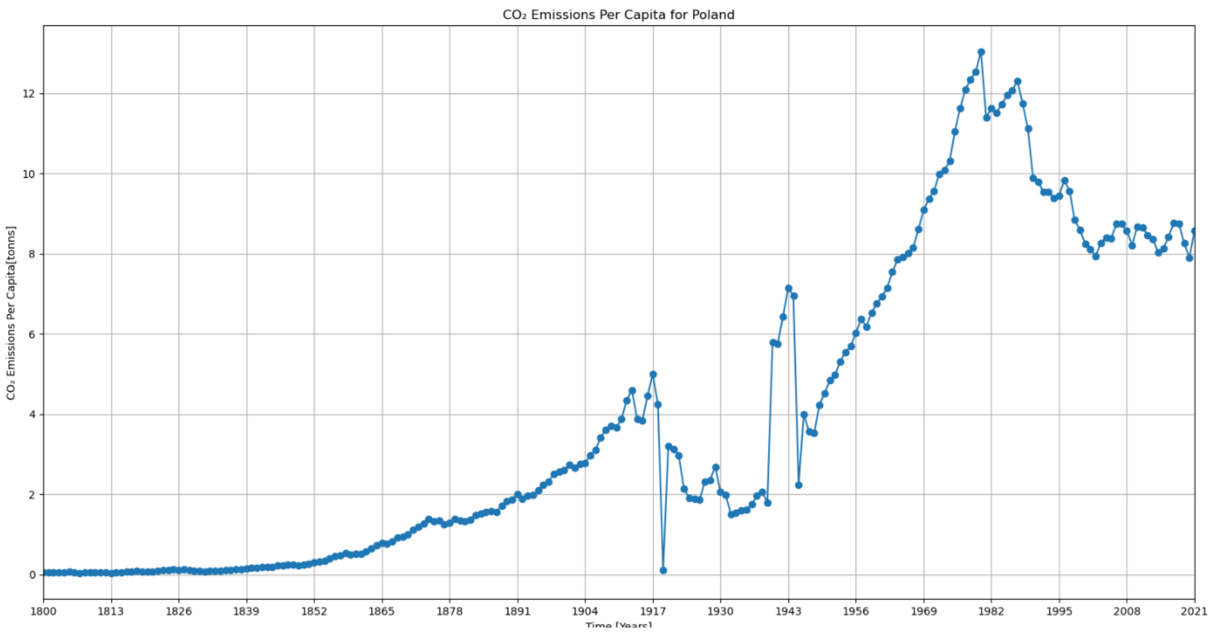


Figure 4.8 - CO_2 emissions per capita over years (2002-2021) in Poland [38]

In the case of the data analyzed above, for example, Sweden, which has a larger area than Poland and almost 4 times fewer inhabitants, will have far fewer overall emissions [33]. This would then not mean that it is very green but would be due to fewer emissive factors (fewer people).

The CO_2 emission rate for Poland since 1800 is shown in Figure 4.8. We can see that from the time of measurement until the end of World War I, the rate was increasing (this was due to the Industrial Revolution). Later, a big jump in emissions was recorded during World War II (similar behavior to WWI) and then after the war until the big economic transition in the 1980s of the 20th century this indicator was rising. Currently, for the past 20 years it has been at a similar level slightly fluctuating between 8-9 [tons] per person. Unfortunately, there are no data yet for 2022, but it is possible that a large decrease in CO_2 emissions will be noticeable in the future. Poland is involved in a number of projects aimed at protecting the environment and centered around renewable energy and nuclear power. In the future, this should bring big benefits in the statistics.

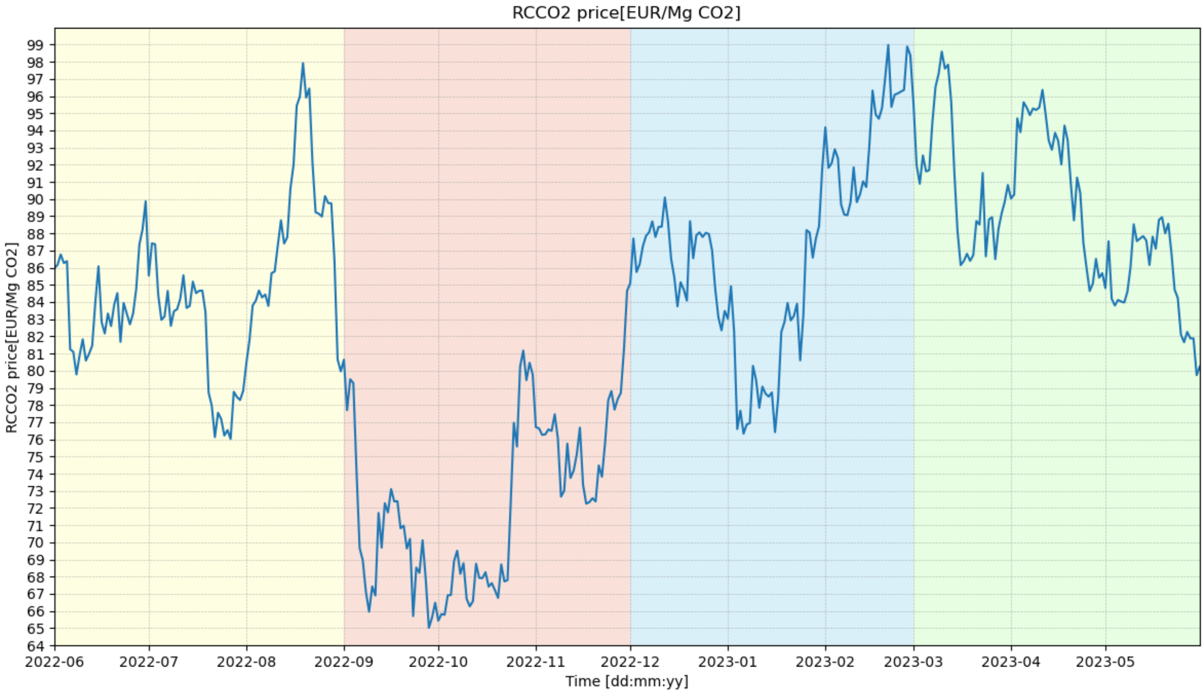


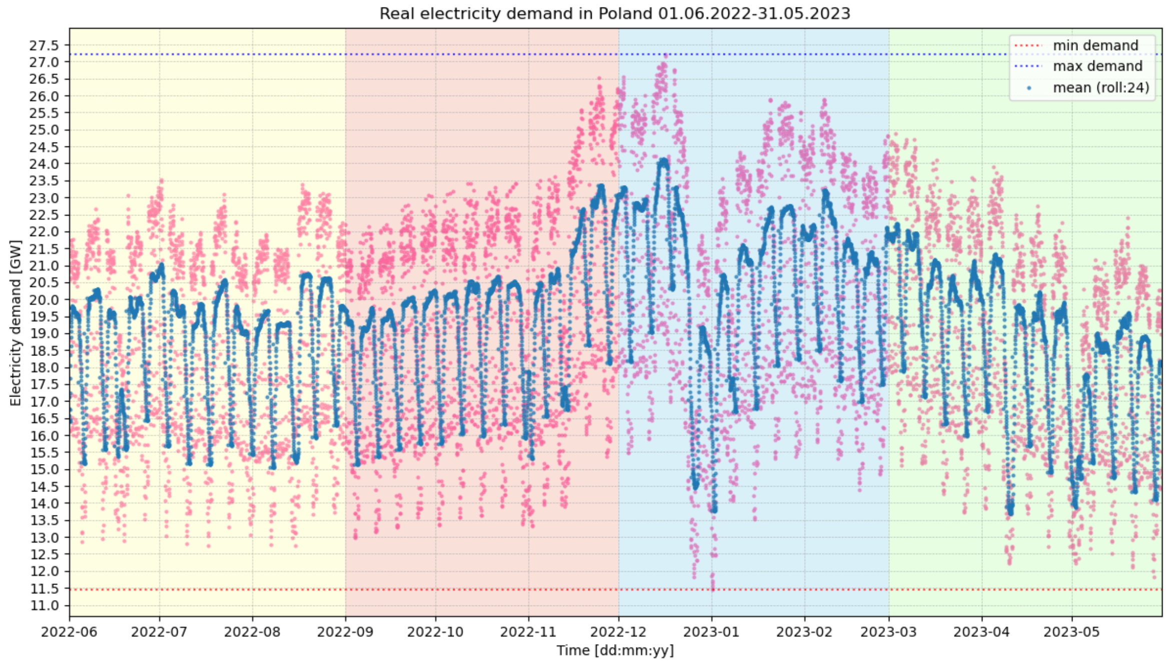
Figure 4.9 - CO_2 stock price [EUR/Mg CO_2 emitted] [own elaboration based on PSE - 34,35]

Since 2005, the EU ETS, or greenhouse gas emission fees, has been in operation in the European Union. At the very beginning, allowances were distributed for free to electricity producers. From year to year the amount of allowances is reduced, which is supposed to lead to lower emissions throughout the EU. [34] After some time, allowance fees were introduced so that less-polluting generators could sell their surplus allowances to more-polluting ones (the total amount of emissions does not change, and the system benefits the more environmentally friendly generators). Since then, the price of allowances has risen significantly (with small drops). The EU is trying to keep the price of allowances at a level that makes it profitable to trade them and invest in renewable sources of emissions rather than risk exceeding the emission cap and incurring penalties. As we can see in Figure 4.9, over the past year the price of allowances has ranged from 65 to almost 100 [EUR] per ton of CO_2 emitted. So there is no doubt that at current energy prices, emission fees are significantly increasing their amount.

4.2 Electricity demand in Poland 06.2022-06.2023 – data from the KSE

As mentioned in previous chapters, Poland is a developing country and its market has been recognized as developed. Among other things, this has resulted in an increase in electricity consumption. This is because the standard of living of citizens is rising and the economy, which is growing dynamically, is also consuming more energy. [35]

Figure 4.10 - demand for electricity in Poland 06.2022-06.2023 in hourly resolutions, with the



seasons of the year [own elaboration based on data from the KSE]

The annual course of electricity demand for Poland is edged by the pink line in Figure 4.10. It is an hourly distribution describing the period from June 2022 to June 2023. The background colors symbolize the seasons, starting, however, not on a calendar basis, but conventionally from the 1st day of each month in which a change occurs (this does not affect the content of the graph and, thanks to this, the data are shown more clearly).

In addition (as the data studied is a time series) its smoothing has been applied here - using the "chronological average" method (Appendix B). I decided to do this because I realize how many factors beyond the season, day of the week, temperature or level of development of a country affect energy demand. This method allowed me to discard measurements related to random events (such as an unexpected weather collapse) and reveal the overall trend of the curve - the blue color. The aggregated curve gave us a beautiful preview of the wear profile. Counting the lower or upper peaks of the blue line, we come out with perfectly 52 of them - exactly how many weeks there are in a year. One such week is highlighted in Figure 4.10 with a black box. The next chart will illuminate more why the box was placed there. What is important at this point is that the method used to "de-noise" the data was successful. It allowed us to extract as many curves similar in shape as there are weeks in a given year. Thus, it can be said with certainty that one section of the graph similar to the one highlighted in the box corresponds to an energy demand curve covering a time period of one week.

As we can see, generally the lowest demand for electricity is recorded in late spring and early summer. This is probably when people stop heating rooms with electricity and the temperatures outside are not so high to use air conditioning. In summer, the profile of the consumption curve is quite repetitive. The closer we get to the end of autumn and the beginning of winter, the greater the increase in energy demand, reaching as much as 3-4 [GWh] autumn to winter, viewed on an hourly basis. The sudden drop in energy demand in late December and early January is related to the holidays. Workplaces are closed then and energy consumption drops significantly.

Considering electricity consumption not in terms but in terms of the day can shed us a little more light on the reason for lower energy consumption on certain days. As we can see in Figure 4.11, definitely less energy is used on weekends than on weekdays. The reason is simple - factories do not operate on weekends. This gives us an idea of what fraction of energy consumption comes from businesses. This conclusion is also confirmed by the fact of lower energy consumption on holidays and days around holidays (e.g. the low blue dots in June and November, just before or after Corpus Christi on 08.06 and All Saints on 02.10). You can also see a large "gap" in the graph at the New Year's Day location.

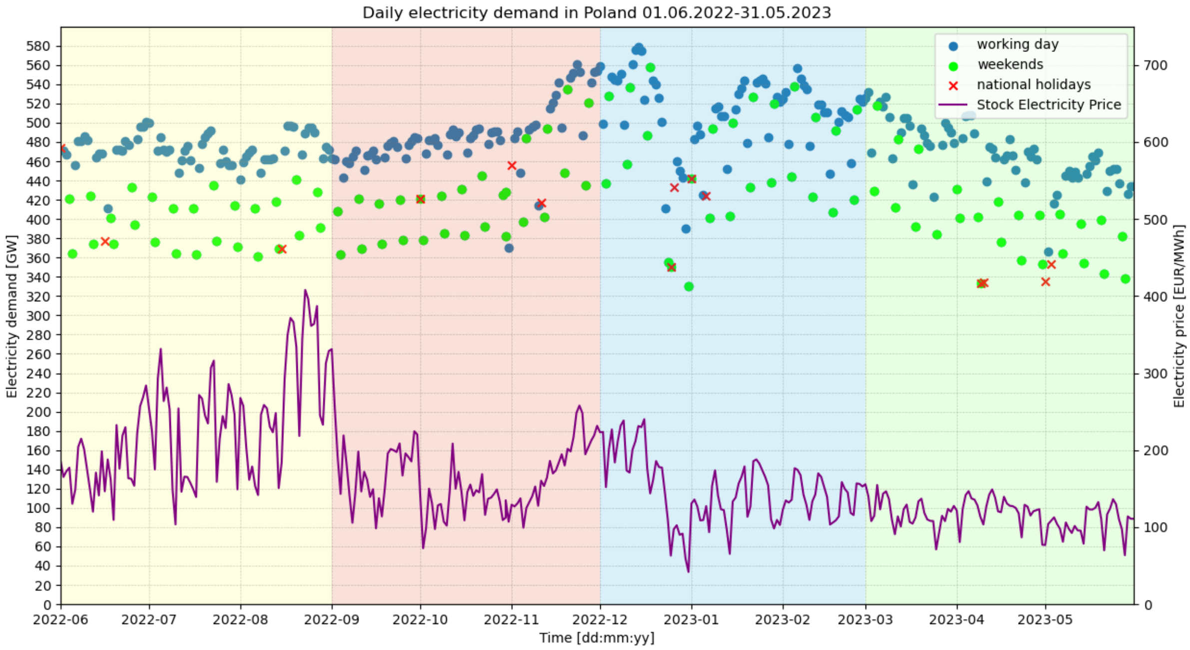


Figure 4.11 – Daily electricity demand in Poland 01.06.2022-31.05.2023 [own elaboration based on data from the KSE]

Of course, the end of December in Poland is the period associated with Christmas and many people go on vacation then and workplaces close for a few days. What's more interesting is that this drop in consumption correlates with the price of energy which falls then. Analyzing this graph from September 2022 to the end of May 2023, it is clear that a drop in energy consumption results in a drop in energy prices. Put perhaps in a better even way, a decrease in demand for energy results in a decrease in prices. An increase in demand for it higher prices. This is in line with the basic law of economics known as the "law of supply and demand" which has already been mentioned here several times.

So summarizing the demand graphs in Figure 4.10 and Figure 4.11, we see that energy demand varies throughout the year. In winter, people use slightly more energy than in summer (increasingly efficient air conditioners and heat pumps have also contributed to this). On top of that, the time of day is an important factor. We can see two peaks in daily energy demand: morning - when people wake up and go to work and school, and evening - when most people return home from work and school. In addition to this, national energy consumption depends on whether the day is a working day, a holiday or a weekend. Measurement results clearly show that on weekends and holidays when factories are not working energy demand is much lower than on weekdays. Long weekends contribute to longer reduced demand.

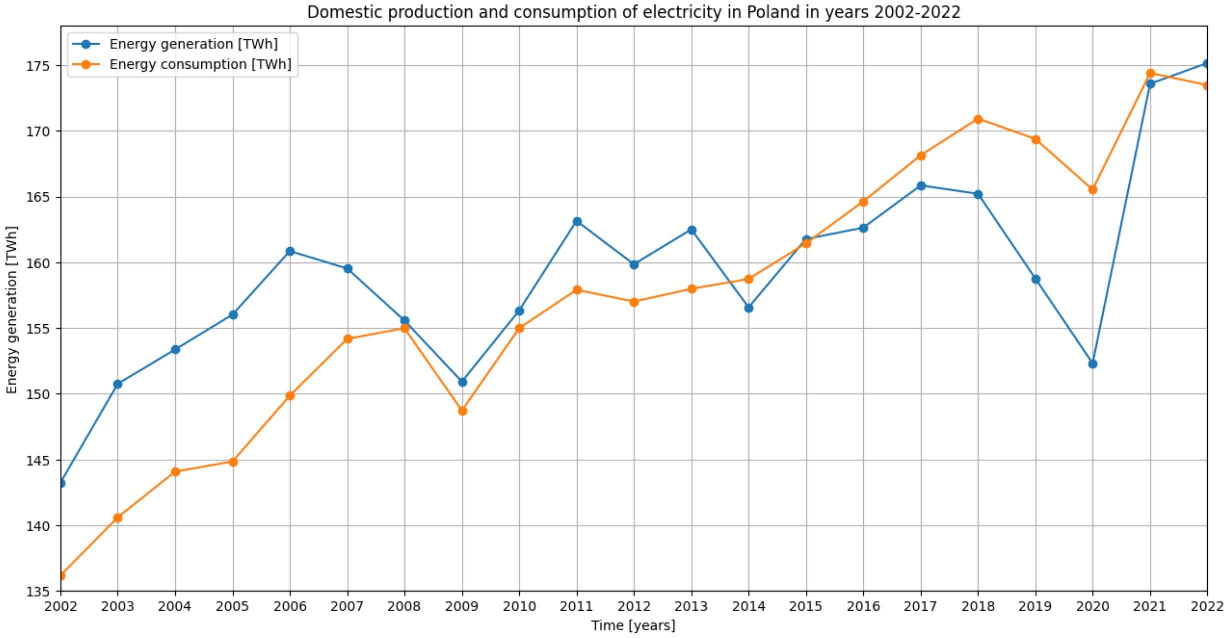


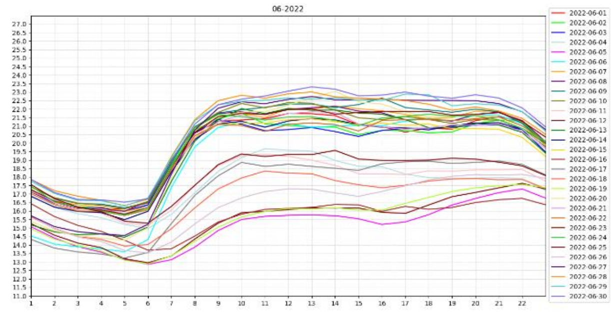
Figure 4.12 - Domestic production and consumption of electricity in Poland in years 2002-2022 (own elaboration based on PSE data) [35]

Electricity demand over the past 20 years for Poland is shown in Figure 4.22. From year to year, the demand for electricity in Poland increases. There are, of course, years that break out of this rule, e.g. 2020 when covid-19 was raging around the world. At that time, most people were working at home and a penny of production facilities was turned off. A second such factor is temperature, for example. Warmer winters reduce energy and heat demand and cooler summers reduce consumption for air conditioning. The upward trend of the consumption curve itself is not surprising. Poland is among the developed and developing countries so industry must consume more and more energy [24].

It is also worth considering the ratio of consumption to energy production in a country. This is an important issue in the context of national security. One must ask oneself whether, if necessary, the country would be able to produce all the necessary energy on its own. In 2022, for the first time in 7 years, Poland's energy production was greater than its consumption. This is a good course of action, supported by the development of heat pumps, onshore wind power and, above all, photovoltaics and energy storage.

In order to make a reliable analysis of the energy demand curves, the hourly daily data cannot be omitted. Each day of the study period is shown in Figure 4.13. This allows us to see with our own eyes the hourly peaks in energy demand mentioned in earlier paragraphs. In the summer months from June to August, the demand curve is flattened the most in the year. The colder the month, the more clearly the demand curve emphasizes the evening peak in demand. It can also be seen that in each month there are a few such days that have decidedly lower demand. These include weekends and holidays. Depending on the season of the year, the demand peaks shift slightly, but as a rule, the morning peak is observed between 6-8 a.m. (that's when people get up for work and school) and the evening peak between 7-21 p.m. The morning peak is much more dangerous for the system because at times it is necessary to increase the power of the operating power plants by up to 5 GW within two hours (that is, it would be like if the power plant in Belchatow had to be started up at an express pace - the problem is that at the moment there is no other way to start up such a large coal-fired power plant from a cold state to full power in such a short time).

However, the operator of the Polish Transmission System must be commended, because it can be seen from the above graphs that, not counting the morning demand spike, the daily curve is flattened for the most part. The more uniform the daily energy consumption is from hour to hour, the easier, better, cheaper and more efficient it is to balance the entire energy system. More efficiently the units can be selected for operation, and they are not subjected to either too much load or too long operation at reduced parameters to keep them in readiness.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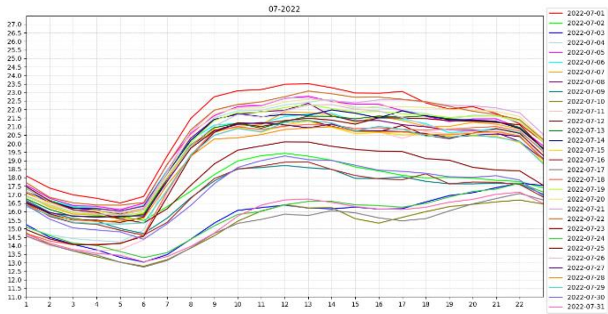
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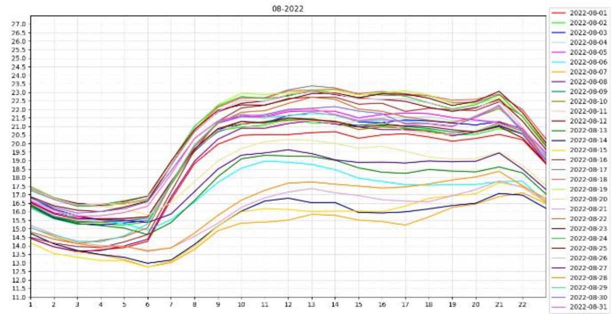
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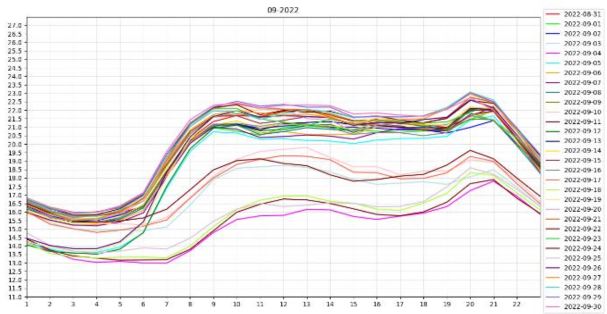
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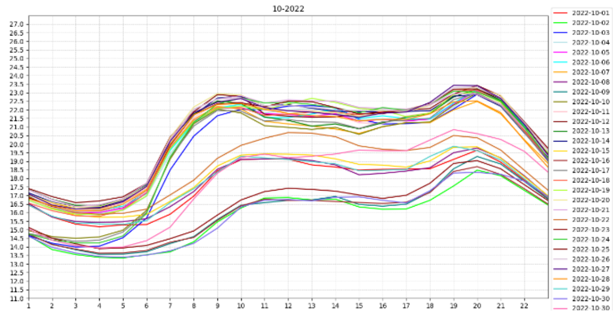
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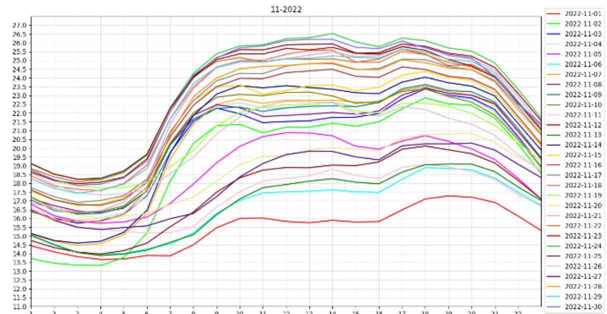
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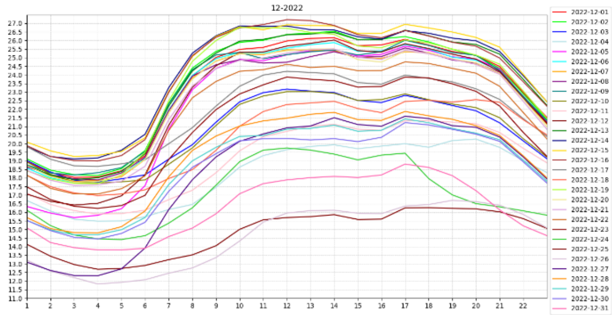
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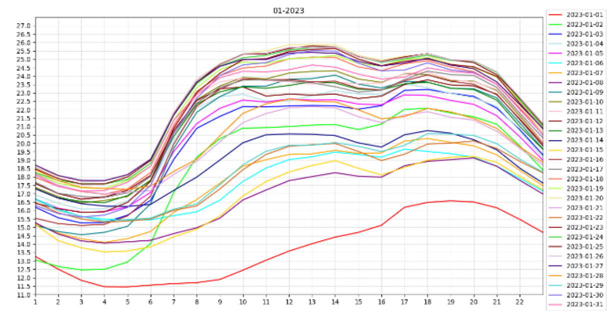
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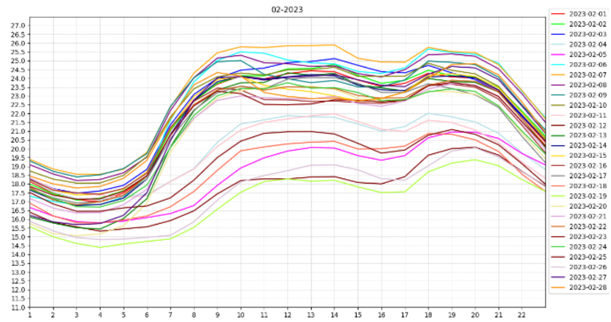
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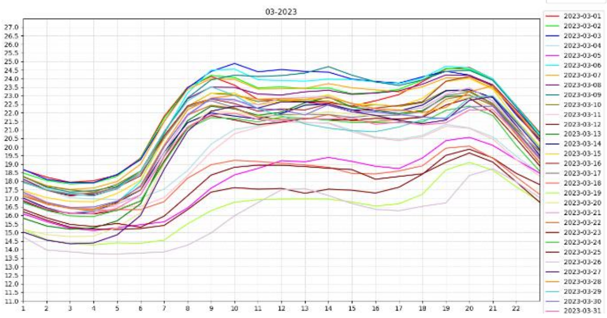
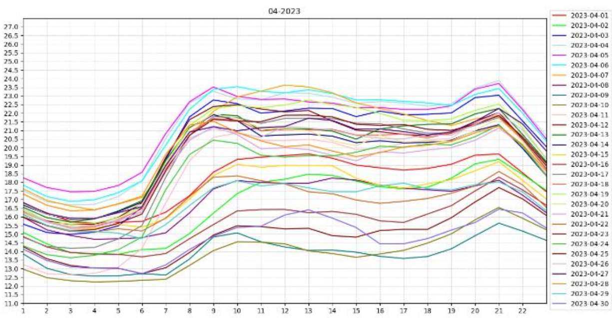

03-2023

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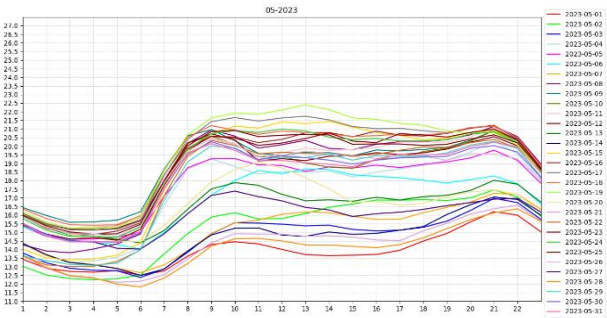

05-2023

Figure 4.13 - Monthly summaries of electricity demand for Poland in the period 06.2022-06.2023; dependence of hourly demand for energy in [GWh] on the hour of the day [own elaboration based on data from PSE]

Assuming that there were about 37.7 million people living in Poland at the end of 2022, and each of them generates its own demand curve continuously, this gives us 37.7 million curves. All curves must be satisfied and the course of none can be predicted exactly. Nevertheless, the transmission system operator must try to meet the needs of everyone and select the operation of generating units in such a way that they both work efficiently and everyone has electricity at home.

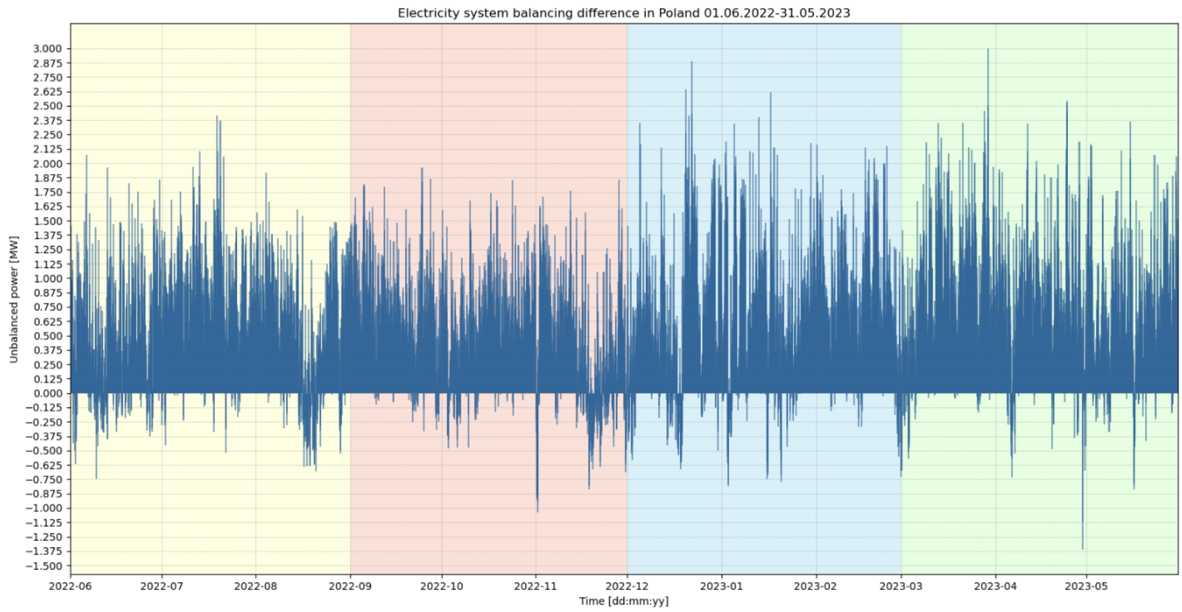


Figure 4.14 - Diagram of the difference between the daily electricity demand forecast for Poland and the actual demand, broken down by seasons [own elaboration based on data from PSE]

Figure 4.14 shows the time distribution of the imbalance of Poland's power system between 06.2022 and 06.2023. The chart clearly shows that oversupply of energy is far more common, which is obviously far better than shortage. Of course, overloading transmission lines can lead to deterioration of power quality or even damage to them, but on the other hand, a shortage of power in the grid threatens a blackout. The greatest oversupply of energy is in winter probably because buyers in the intraday market declare larger purchases for fear of greater consumption (e.g., for space heating). Then the next day on the Balancing Market it turns out that such an amount of energy is not needed and there is then an oversupply. Those who declared too small purchases the previous day can therefore buy "unnecessary" energy for others cheaper than the day before. Energy shortages on the market, on the other hand, are mainly due to three reasons. Firstly, when buyers declare lower than actual energy consumption on the market the next day and the next day, for example, due to cooling or even high heat, they need more energy. The second reason is incorrect estimates of the actual amount of energy we can get from photovoltaics and wind turbines. In fact, they generate the greatest instability in the market because it is impossible to accurately predict their production. The more of these units there are in the energy system, the harder it is to stabilize it, but they are necessary to reduce greenhouse gas emissions from power generation. The third case is block failures in controllable power plants. Often, too, during holidays or long weekends, due to the anticipated lower consumption of electricity, large power units are shut down for maintenance or repair (and by that time they are operating, for example, only at half their possible capacity) [36], [37]. During the period under review, the following shutdowns listed in Table 4.6, among others, occurred. Also of concern are the calculations of specialists, who say that from January to early November 2022, on average, more than 40% of the achievable capacity in coal-fired units was unavailable each hour. In addition to shutdowns and failures at Polish power plants, shortages in coal supplies for the power industry added to the problems [38]. In such a situation, we have to bail out by importing energy from other countries, and we are fortunate that we have several good neighbors who are willing to sell us this energy in times of need.

The summed system data shows that in the period between 01.06.2022 and 31-05.20223 the sum of "surplus" power amounted to 5503.019 [GW] and "deficiency" power 210.22 [GW]. This gives, in turn, 3.25% surplus to the total demand (which, let us remind you, amounted to 169.24 [TWh] according to data from the NPS) and 0.12% power shortage, i.e. the Polish power system was balanced in 99.98%. Even so, sudden failures of 1 GW of power plant units like those repositioned in Table 4.6 can shake the system because this is a vial of 0.5 -0.8% of hourly production.

Table 4.6 - Examples of power plant unit shutdowns in Poland

Date	**Name of power plant (town)**	**Reason of shutdown**	**Power of units shut down [MW]**	**Time of outage**
24-01-2023	Jaworzno	emergency outage of one of the mills	910	2 dni

21-12-2022	Kozienice	steam system malfunction	1075	2 tygodnie
08-2022	Jaworzno	Pollution in the power plant block - daily stoppages of the feeder belt and failures of some equipment working in the block	910	Short, irregular periods

Source: own elaboration based on [36], [39], [40]

We can still look at the graph of the density distribution of the occurrence of given loads on the grid during the period I studied. I have presented it in the form of a histogram in Figure 4.15. We can see that the most frequent occurrence of energy demand was about 16 [GWh] and 21 [GW]. Presumably, these two values are equal to the morning peak and the evening peak on the energy demand curve.

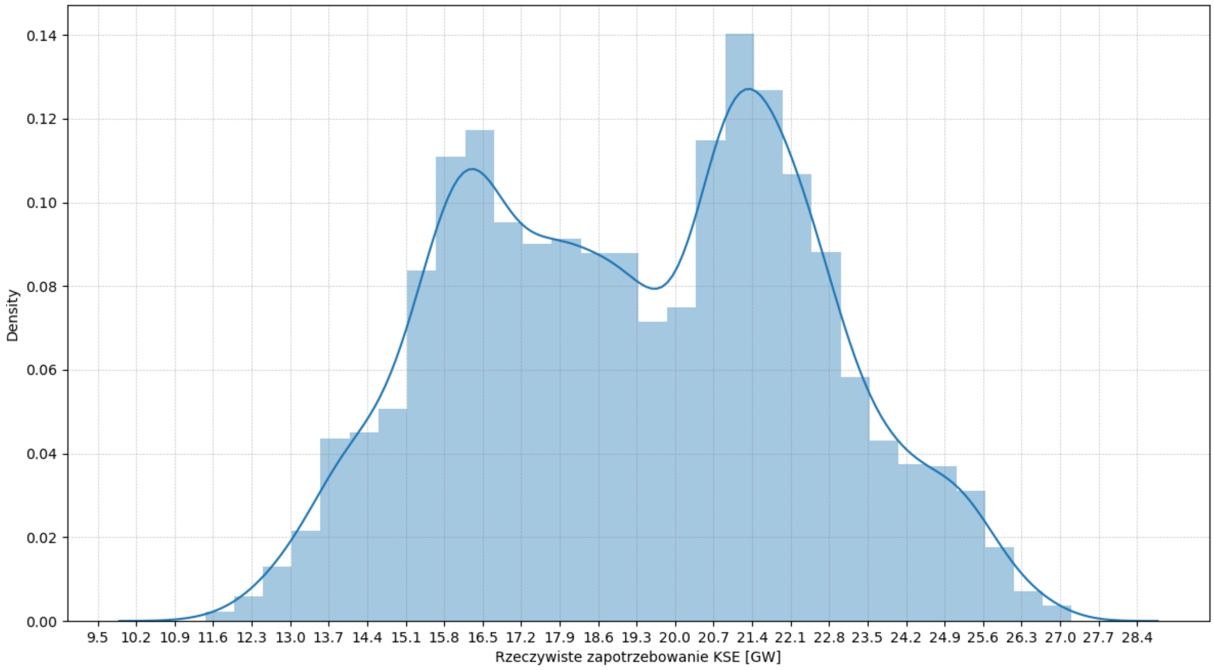


Figure 4.15 - Density distribution of specific energy demand values for Poland in the period 06.2022-06.2023 [own elaboration based on data from PSE]

4.2.1 Energy mix and generation structure in Poland at the end of 2022 year

Poland is becoming a greener country every year. We are a member of the EU and are taking part in its green transformation. The basis for reducing environmentally poisonous greenhouse gases is to reduce the consumption of coal and lignite. In order to compare Poland's progress over the last year, in Table 4.7 and Table 4.8 I have summarized the energy mix and the structure of energy generation by source. Of course, in making the comparison we have to keep in mind that we are comparing the entire year 2022 versus the first half of 2023 (which admittedly includes a chunk of winter and spring but omits autumn and cold December) so the relative progress at the end of the year may be greater and the final year generation structure slightly different. Despite these imperfections, I think it's worth leaning into because comparing these parameters can help us draw interesting conclusions already at this stage.

Table 4.7 - Poland's energy mix [46,47,48]

Name of technology	**% share in Poland's mix in 2022**	**% share in Poland's mix in 2023**	**installed capacity 31.12.2022 [GW]**	**installed capacity 31.05.2023 [GW]**
hard coal	36,4	34,3	21,45	21,47
lignite	15,1	14,2	8,91	8,91
photovoltaics	20,7	22,2	12,19	13,9
onshore wind	14,0	14,0	8,26	8,76
hydroelectric + pumped storage power plants	3,9	3,7	2,31	2,29
natural gas	6,3	6,4	3,74	4,03
Biofuels (biomass + biogas)	1,9	2,0	1,12	1,26
others	1,7	3,1	1,01	1,95
nuclear	0	0	0	0
Total installed capacity [GW]			**58,99**	**62,57**
Annual energy demand [TWh]			**169,24**	**-**

Source: own elaboration based on [41]–[43]

As we can see in Table 4.7 in the first half of 2023, production from hard coal increased somewhat. Of course, this conflicts with what was said earlier that Poland is moving away from coal. However, half-year results are not precisely an accurate indicator. Poland is also seeing the replacement of wind turbines with newer ones, as well as repairs and breakdowns of other power plants. It is likely that somewhere around the turn of the year additional coal-fired power plants had to be put into operation working behind others that were out of order. A slight increase in coal capacity is therefore nothing to worry about and does not mean that Poland is moving in the wrong direction. We have the same amount of capacity in lignite. Onshore wind capacity increased by 0.5 [GW] in six months. And hydroelectric power capacity fell by 0.2 [GW]. Pumped storage power plants are very important storage facilities in our system because large amounts of energy can be released from them very quickly. This energy to be stored can come, for example, from photovoltaics whose capacity increased by almost 2 [GW] in six months. There was also a slight increase in the capacity located in gas, biomass and biogas power plants and other small-scale power plants. The total installed capacity of all power plants in the country increased by about 3.6 [GW] in six months, of which 2.5 [GW] are renewable technologies. Energy consumption, on the other hand, amounted to nearly 170 [TWh].

Table 4.8 - Electricity generation in Poland, broken down by source at the end of 2022 in comparison with first half of 2023

Name of the technology	**% share of energy production 2022**	**% share in energy production 01-05.2023**	**energy production [TWh] in 2022**
hard coal	42,6	38,9	79
lignite	26,5	21	47,3
photovoltaics	4,5	5,4	8
onshore wind	10,8	14,5	19,4
hydroelectric + pumped storage power plants	1,7	2,6	3,1
natural gas	3,3	5,6	11,7
Biofuels (biomass + biogas)	4,2	4,7	7,6
others	6,4	7,3	2,9
nuclear	0	0	0
Gross domestic yearly electricity production [TWh]			**178,8**

Source: own elaboration based on [42]

Installed capacity is one thing, but which power plants Poland's electricity actually comes from is another and far more important matter. These data are presented in Table 4.8. When we juxtapose them with Table 4.7 we can see that despite the increase in installed capacity in hard coal in the first half of 2023, energy production from this source fell by 3.7 percentage points and total production from coal by as much as 9.2 percentage points (in 2022 production from coal was almost 70% of total production and in 2023 almost 60%). The opposite situation is with pumped storage power plants which, despite the decline in their installed capacity, generated more energy than in the previous year. The share of renewable power plants has also increased, of course. By far the most energy is produced from onshore wind power plants than from photovoltaics of which we have 4 [GW] more in the system. This is due to Poland's climate zone. Definitely for more time during the day it is windy than sunny or the radiation is so weak that photovoltaic panels cannot operate with satisfactory power.

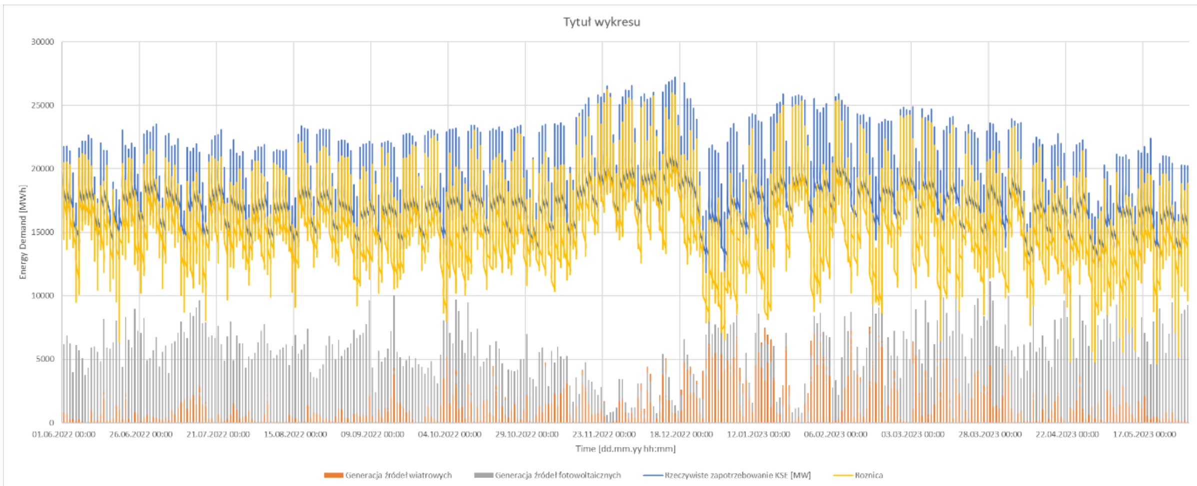


Figure 4.16 - Wind and PV generation in 01.06.2022-31.05.2023 compare to residual load and electricity demand in Poland [own elaboration based on PSE data]

In 2022, Polish power plants produced a total of almost 179 [TWh] of electricity, which means that domestic production was about 10 [TWh] higher than domestic consumption. Of course, this does not mean that without imports we would be a completely sufficient country. Renewable energy plants produce about 20% of the annual energy demand of which most of the time production does not temporarily coincide with immediate consumption. This trend is shown in the graph in Figure 4.16. We can see that especially in the winter months, when we have the highest consumption of electricity, the generation from RES is the lowest. Therefore, all the time scientists are working on efficient energy storage so that it can be accumulated in summer (when conditions for RES energy production are better) and used in winter.

4.3 Research - Application 1 "Merit Order Simulation”

4.3.1 Default parameters used in the simulation for Poland

Taking into account the comparison of LCOE costs from Tab 3,4,5 for further analysis for Poland I will rely on the following data from Tab 8 and Tab 9 . The prices included in the tables do not include the cost of CO_2 emissions because these costs will separately count already directly in the simulation.

Table 4.9 - Summary data for market simulation: LCOE cost data used in the simulation (self-development based on previously reported data).

Technology	Price [EUR/MWh]
Wind on-shore	50
Photovoltaic	52
Hard coal	70
Lignite	155
Natural gas CCGT	90
Nuclear	102
Hydro >=10 MW	110
Biofuel (overall)	76

Source: own elaboration based

In addition, I have assumed the following energy mix for Poland, consistent with the mix as of 31.05.2023 shown in Table 4.7. In addition, I have assumed the following emission factors for different types of power plants and their efficiencies shown in Table 4.10.

Table 4.10 - CO_2 emissivity starting data for simulation for Poland

Technology	Emission factor [kg/GJ]	Power plant efficiency [%]
Solar	0	100
Wind	0	100
Hydro	0	100
Coal	93.54	46
Gas	55.48	58
Brown Coal	111.53	44
Nuclear	0	36
Biofuel	0	100

Source: own elaboration based on [15], [44]

In addition, the price of CO_2 emission permits was taken as the price on the last day of the study period, i.e. on 31.05.2023, and amounted to 80.24 $\left[\frac{EUR}{tonn\ CO_2}\right]$ [34].

The application simulating merit order energy pricing allows us to track price changes depending on the country's energy mix and the advancement of power plant technology.

In Poland, we have 2 national strategic documents for the energy sector:

- "National Energy and Climate Plan for 2021-2030".

- "Energy Policy of Poland until 2040 ".

Due to the fact that both of these documents need to be updated in the second half of 2023 (among other things, due to a much faster than assumed increase in the share of photovoltaics in the Polish mix - exceeded 10 years earlier - and a several-fold increase in the price of CO_2 ETS) if there is a possibility, I will select parameters for the study from other available sources.

The first source from which I took electricity demand forecasts was a document based on the two previously mentioned called "Development Plan for Meeting Current and Future Electricity Demand for 2023-2032" created by PSE in November 2023. [51] As shown in Figure 4.17, 2 variants will be considered: baseline and increased electricity demand. The demand I'm taking into account is in red on the chart and includes predictions for the rise in popularity of electric cars and heat pumps.

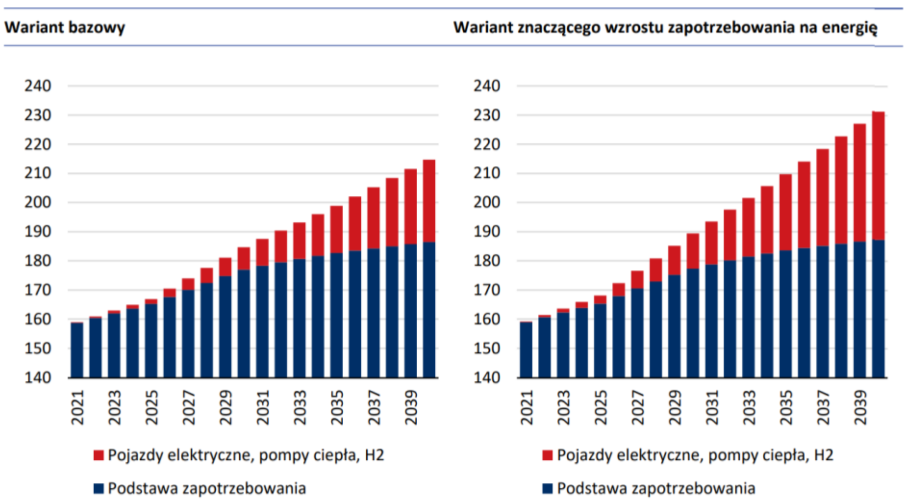


Figure 4.17 - Annual net electricity demand in 2021-2040 [TWh]; left – base case, right - significant increase in demand case

The installed capacity projected for future years was taken from the document "National Energy and Climate Plan 2021-2030" and can be found in Table 4.11 . I took data from this table for the years 2025-2040. I treated old and new power plants as the same source. Pumped and hydroelectric power plants too. I left out thermal power plants and other types of power plants signed as "tur.gas./cold rez./import m.".

Table 4.11 - Net maximum capacity of electricity generation sources by technology [MW]

	2005	2010	2015	2020	2025	2030	2035	2040
el. na węgiel brunatny – stare	8 197	8 145	8 643	7 669	7 060	7 060	4 827	2 492
el. na węgiel brunatny – nowe	0	0	0	455	455	455	455	455
el. na węgiel kamienny – stare	14 613	14 655	13 617	11 975	11 672	9 408	5 005	2 450
el. na węgiel kamienny – nowe	0	0	0	3 497	4 422	4 422	4 422	4 422
el. na gaz ziemny	0	0	0	0	0	0	700	1 989
el. jądrowe	0	0	0	0	0	0	1 500	4 500
el. wodne	1 064	935	964	1 002	1 049	1 175	1 225	1 275
el. pompowe	1 256	1 405	1 405	1 405	1 405	1 405	1 405	1 405
ec. przemysłowe	6140	6126	1 925	1 975	1 879	1 745	1 810	1 836
ec. na węgiel kamienny			4 046	4 291	4 169	3 876	3 232	2 426
ec. na gaz ziemny	760	807	928	2 687	3 137	3 297	5 481	6 319
el. i ec. na biomasę	102	140	553	649	873	1 146	1 416	1 763
ec. na biogaz			216	319	439	556	649	707
el. wiatrowe	121	1 108	4 886	6 088	7 625	10 004	12 688	13 910
fotowoltaika	0	0	108	613	1 238	1 863	2 488	3 037
turb.gaz./ zimna rez./ import m.	0	0	0	0	0	0	1 116	1 965

Source: own elaboration based on [15]

In Table 4.12 the energy mix parameters are shown for successive simulation cases and in Table 4.13 the emission factors are shown. If only a few parameters change between successive simulations it is highlighted in gray.

Table 4.12 - Power plants capacities for different simulation cases

No.	year	Installed capacity [GW]							
		hardcoal	lignite	pv	on-shore	hydro	gas	biofuels	atom
1	2025	16,1	7,5	1,2	7,6	2,5	3,1	1,3	0
2	2030	13,8	7,5	1,9	10,0	2,6	3,3	1,7	0
3	2035	9,4	5,3	2,5	12,7	2,6	6,2	2,1	1,5
4	2040	6,9	2,9	3,0	13,9	2,7	8,3	2,5	4,5
5	2025	16,1	7,5	1,2	7,6	2,5	3,1	1,3	0
6	2030	13,8	7,5	1,9	10,0	2,6	3,3	1,7	0
7	2035	9,4	5,3	2,5	12,7	2,6	6,2	2,1	1,5
8	2040	6,9	2,9	3,0	13,9	2,7	8,3	2,5	4,5
9	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
10	2026	21,5	8,9	16,7	8,3	2,3	4,0	1,3	0,0
11	2026	21,5	8,9	21,8	8,3	2,3	4,0	1,3	0,0
12	2026	21,5	8,9	29,8	8,3	2,3	4,0	1,3	0,0

13	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	1,6
14	2033	21,5	8,9	34,1	8,3	2,3	4,0	1,3	1,6
15	2033	21,5	8,9	34,1	8,3	2,3	4,0	1,3	1,6
16	2025	16,1	7,5	0,3	4,5	2,5	3,1	1,3	0
17	2030	13,8	7,5	0,4	5,9	2,6	3,3	1,7	0
18	2035	9,4	5,3	0,5	7,5	2,6	6,2	2,1	1,5
19	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
20	2025	16,1	7,5	0,3	4,5	2,5	3,1	1,3	0
21	2030	13,8	7,5	0,4	5,9	2,6	3,3	1,7	0
22	2035	9,4	5,3	0,5	7,5	2,6	6,2	2,1	1,5
23	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
24	2023	21,5	8,9	3,0	4,9	2,3	4,0	1,3	0
25	2026	21,5	8,9	3,6	4,9	2,3	4,0	1,3	0
26	2026	21,5	8,9	4,7	4,9	2,3	4,0	1,3	0
27	2026	21,5	8,9	6,5	4,9	2,3	4,0	1,3	0
28	2023	21,5	8,9	3,0	4,9	2,3	4,0	1,3	1,6
29	2033	21,5	8,9	7,4	4,9	2,3	4,0	1,3	1,6
30	2033	21,5	8,9	7,4	4,9	2,3	4,0	1,3	1,6
31	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
32	2033	21,5	8,9	34,1	8,3	2,3	4,0	1,3	1,6
33	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
34	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
35	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
36	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
37	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
38	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
39	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
40	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
41	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
42	2023	21,5	8,9	13,9	8,3	2,3	4,0	1,3	0,0
43	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
44	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
45	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
46	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
47	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
48	2040	6,9	2,9	0,7	8,2	2,7	8,3	2,5	4,5
49	2023	21,5	8,9	0	0	2,3	4,0	1,3	0,0
50	2040	6,9	2,9	0	0	2,7	8,3	2,5	4,5

Source: own elaboration based on [15]

Table 4.13 - Co2 emission factors for different simulation cases

No.	Base case	Year	CO_2 emission factors [kg/GJ]							
			hardcoal	lignite	pv	on-shore	hydro	gas	biofuels	atom
31	9	2023	93,54	111,53	0	0	0	55,48	0	0
32	19n	2040	93,54	111,53	0	0	0	55,48	0	0
33	15	2033	93,54	111,53	0	0	0	55,48	0	0

34	9	2023	88,86	105,95	0	0	0	52,71	0	0
35	9	2023	84,19	100,38	0	0	0	49,93	0	0
36	9	2023	79,51	94,80	0	0	0	47,16	0	0
37	19n	2040	88,86	105,95	0	0	0	52,71	0	0
38	19n	2040	84,19	100,38	0	0	0	49,93	0	0
39	19n	2040	79,51	94,80	0	0	0	47,16	0	0
40	9	2023	93,54	111,53	0	0	0	55,48	0	0
41	9	2023	93,54	111,53	0	0	0	55,48	0	0
42	9	2023	93,54	111,53	0	0	0	55,48	0	0
43	19n	2040	79,51	94,80	0	0	0	47,16	0	0
44	19n	2040	79,51	94,80	0	0	0	47,16	0	0
45	19n	2040	79,51	94,80	0	0	0	47,16	0	0
46	19n	2040	93,54	111,53	0	0	0	55,48	0	0
47	19n	2040	65,48	111,53	0	0	0	55,48	0	0
48	19n	2040	93,54	111,53	0	0	0	55,48	0	0
49	9	2023	93,54	111,53	0	0	0	55,48	0	0
50	19n	2040	93,54	111,53	0	0	0	55,48	0	0
No	**Base case**	**Year**	**Power plants efficiency [%]**							
			hardcoal	**lignite**	**pv**	**on-shore**	**hydro**	**gas**	**biofuels**	**atom**
31	9	2023	46	44	100	100	100	58	85	36
32	19n	2040	46	44	100	100	100	58	85	36
33	15	2033	46	44	100	100	100	58	85	36
34	9	2023	46	44	100	100	100	58	85	36
35	9	2023	46	44	100	100	100	58	85	36
36	9	2023	46	44	100	100	100	58	85	36
37	19n	2040	46	44	100	100	100	58	85	36
38	19n	2040	46	44	100	100	100	58	85	36
39	19n	2040	46	44	100	100	100	58	85	36
40	9	2023	48	46	100	100	100	61	89	38
41	9	2023	51	48	100	100	100	64	94	40
42	9	2023	53	51	100	100	100	67	98	41
43	19n	2040	48	46	100	100	100	61	89	38
44	19n	2040	51	48	100	100	100	64	94	40
45	19n	2040	53	51	100	100	100	67	98	41
46	19n	2040	76	44	100	100	100	58	85	36
47	19n	2040	46	44	100	100	100	58	85	36
48	19n	2040	46	44	100	100	100	58	85	36
49	9	2023	46	44	100	100	100	58	85	36
50	19n	2040	46	44	100	100	100	58	85	36

Source: own elaboration

In addition to setting the installed capacity of each type of power plant, it is also necessary to specify the energy demand for the case. Depending on the year for which the data is done simulation took its projected demand and calculated according to the formula (2):

$$\text{av el. demand} = \frac{\text{el.Demand}\left[\frac{\text{TWh}}{\text{year}}\right]*1000}{365*24}\left[\frac{\text{GWh}}{\text{hour}}\right] \tag{2}$$

Where:

av el.demand – average hourly energy demand $\left[\frac{\text{GWh}}{\text{hour}}\right]$

el.Demand – average annual energy demand $\left[\frac{\text{TWh}}{\text{year}}\right]$

In addition, for some cases marked with *, the generation from a given source has been specifically reduced. This applies to photovoltaics and wind. From Table 4.8, the % share from the energy production of these sources was taken and divided by the percentage of them in Poland's installed capacity. This gives us more realistic capacities that can be considered in terms of merit order, because while controllable power plants can be set to the capacities needed, production from non-controllable sources can only be estimated, and there is virtually no chance that it will ever be 100%. The idea is to treat the estimated installed capacities in consideration of the real yield from them. The calculated ratios of these variables are shown in equations 3a - wind and 3b - photovoltaic.

$$coeffP_{real_{wind}} = \frac{wind\ share\ in\ energy\ production\ [\%]}{wind\ share\ in\ all\ Poland\ power\ capacity\ [\%]} = \frac{8{,}26\ [\%]}{14\ [\%]} = 0{,}59 \tag{3a}$$

$$coeffP_{real_{PV}} = \frac{PV\ share\ in\ energy\ production\ [\%]}{PV\ share\ in\ all\ Poland\ power\ capacity\ [\%]} = \frac{4{,}5\ [\%]}{20{,}7\ [\%]} = 0{,}22 \tag{3b}$$

Then the wind and PV powers from cases 1-15 were multiplied by these coefficients. An example of the equations for the first case 1 is presented in equations 4a - wind and 4b - PV. The result of the action of these equations are the assumed powers for case 16.

$$P_{real_{wind}} = coeffP_{real_{wind}} * P_{case_{wind}} = 0{,}59 * 7{,}6\ [GW] = 0{,}3\ [GW] \tag{3a}$$

$$P_{real_{PV}} = coeffP_{real_{PV}} * P_{case_{PV}} = 0{,}22 * 1{,}2\ [GW] = 4{,}5\ [GW] \tag{3b}$$

*Table 4.14 - Electricity demand for different simulation cases and variants decription (In variants other than ** I assume that Poland has no nuclear power plants. In addition, in variants with ** I assume that the installed capacity of photovoltaics will be as projected for 2027.; In case 48, the ETS CO_2 price is 56.17 [EUR/MWh]; Unless otherwise written, the phrase "base year" means 2023)*

No	el. Demand [TWh/yr]	av el. demand [GWh/hr]	source	Case description
1	167	19,1	[46]	Base + normal energy demand
2	185	21,1	[46]	Base + normal energy demand
3	199	22,7	[46]	Base + normal energy demand
4	214	24,4	[46]	Base + normal energy demand

5	169	19,3	[46]	significant increase in energy demand
6	190	21,7	[46]	significant increase in energy demand
7	210	24,0	[46]	significant increase in energy demand
8	230	26,3	[46]	significant increase in energy demand
9	170,0	20,0	[46]	current status in Poland as of 2023
10	170,0	20,0	[47]	current state in Poland 2023 + photovoltaic as in 2026 - low
11	170,0	20,0	[47]	current state in Poland 2023 + photovoltaic as in 2026 – medium
12	170,0	20,0	[47]	current state in Poland 2023 + photovoltaic as in 2026 - high
13	170,0	20,0	[47]	nuclear power plant today
14	192,0	21,9	[46,47]	nuclear power plant in 2033, rest as in 2022, photovoltaic in 2027-baseline **
15	201,0	22,9	[46,47]	Nuclear power plant in 2033, rest as in 2022, photovoltaic in 2027-high **
16	167	19,1	[46]	pv + wind considering % of production *
17	185	21,1	[46]	pv + wind considering % of production *
18	199	22,7	[46]	pv + wind considering % of production *
19	214	24,4	[46]	pv + wind considering % of production *
20	169	19,3	[46]	pv + wind considering % of production *
21	190	21,7	[46]	pv + wind considering % of production *
22	210	24,0	[46]	pv + wind considering % of production *
23	230	26,3	[46]	pv + wind considering % of production *
24	170	20,0	[46]	pv + wind considering % of production *
25	170	20,0	[47]	pv + wind considering % of production *
26	170	20,0	[47]	pv + wind considering % of production *
27	170	20,0	[47]	pv + wind considering % of production *
28	170	20,0	[47]	pv + wind considering % of production *
29	192	21,8	[46,47]	pv + wind considering % of production *
30	201	22,8	[46,47]	pv + wind considering % of production *
31	170	20,5	[46,15]	base year + CO_2 baseline factor
32	170	20,5	[46,15]	year 2040 + CO_2 base factor
33	170	22,8	[46,15]	year 2033 + CO_2 base factor
34	170	20,5	[46,15]	base year + CO_2 base factor (-5) [%]
35	170	20,5	[46,15]	base year + CO_2 base factor (-10) [%]
36	170	20,5	[46,15]	base year + CO_2 base factor (-15) [%]
37	170	20,5	[46,15]	year 2040 + CO_2 base factor (-5) [%]
38	170	20,5	[46,15]	year 2040 + CO_2 base factor (-10) [%]
39	170	20,5	[46,15]	year 2040 + CO_2 base factor (-15) [%]
40	170	20,5	[46,15]	base year + efficiency of all power plants (+5) [%]
41	170	20,5	[46,15]	base year + efficiency of all power plants (+10) [%]
42	170	20,5	[46,15]	base year + efficiency of all power plants (+15) [%]
43	170	20,5	[46,15]	year 2040 + efficiency of all power plants (+5) [%]
44	170	20,5	[46,15]	year 2040 + efficiency of all power plants (+10) [%]

45	170	20,5	[51,15]	year 2040 + efficiency of all power plants (+15) [%]
46	170	20,5	[51,15]	year 2040 + efficiency of coal-fired power plant (+30) [%]
47	170	20,5	[51,15]	year 2040 + CO_2 baseline factor of coal-fired power plant (-30) [%]
48	170	20,5	[51,15]	year 2040 + emission price (-30) [%]
49	170	20,5	[51,15]	year 2023 – zero wiatr i PV
50	170	20,5	[51,15]	year 2040 – zero wiatr i PV

Source: own elaboration based on [45]

The result of the simulation will be the calculation of how much energy comes from which type of power plant, the final price of energy, the price of CO_2 emissions and the total social welfare - with the selected energy demand.

Social welfare was calculated as the difference between the final price of energy and the prices proposed by producers multiplied by the power proposed in the market for the technology (Equation 4).

$$SW = \sum_{n}^{i=1} (MCP - P_i) * Cap_i \quad (4)$$

Where:

SW – social welfare $[EUR]$

MCP – market clearing price $\left[\frac{EUR}{MWh}\right]$

P_i – price of energy in the following technologies $\left[\frac{EUR}{MWh}\right]$

Cap_i – power available with the technology $[MWh]$

The price of CO_2 emissions was calculated based on the following formulas 5.1, 5.2 and 5.3 .

First, the amount of fuel needed to produce a certain amount of energy was calculated, assuming different efficiency of the power plant (formula 5.1).

$$E_{eff} = \frac{E*3,6}{\left(\frac{eff}{100}\right)} \; [GJ] \quad (5.1)$$

Where:

E_{eff} – how much power is realistically needed in a given source to produce the desired amount of energy, taking into account the efficiency of the power plant; [GJ]

E - the original amount of energy produced of a given power plant [MWh]

eff – efficiency of a given type of power plant [%]

Then count the mass of CO_2 emitted, according to the formula 5.2 .

$$CO_{2_{emiss}} = \frac{coeff * E_{eff}}{1000} \; [tonne] \qquad (5.2)$$

Where:

$CO_{2_{emiss}}$ – the amount of CO_2 emitted during energy production from a given source [kg]

$coeff$ – emission factor appropriately selected for the type of power plant $\left[\frac{kg}{GJ}\right]$

At the very end, to find out the cost of ETS fees for CO_2 emissions, we should multiply the volume of emissions by the unit cost of the emission permit. Exactly as in formula (5.3).

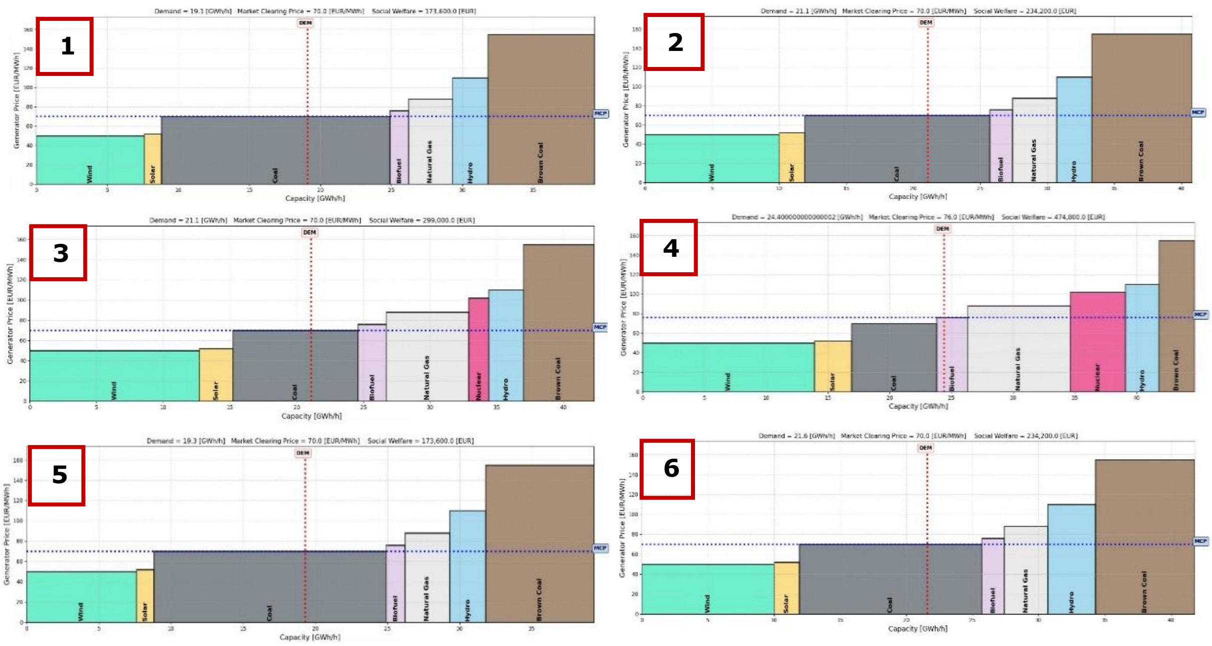
In all my simulations, the ETS unit cost was taken as 80,24 $\left[\frac{EUR}{Mg\ CO_2}\right]$ i.e. the clearing price as of 31.05.2023. [54]

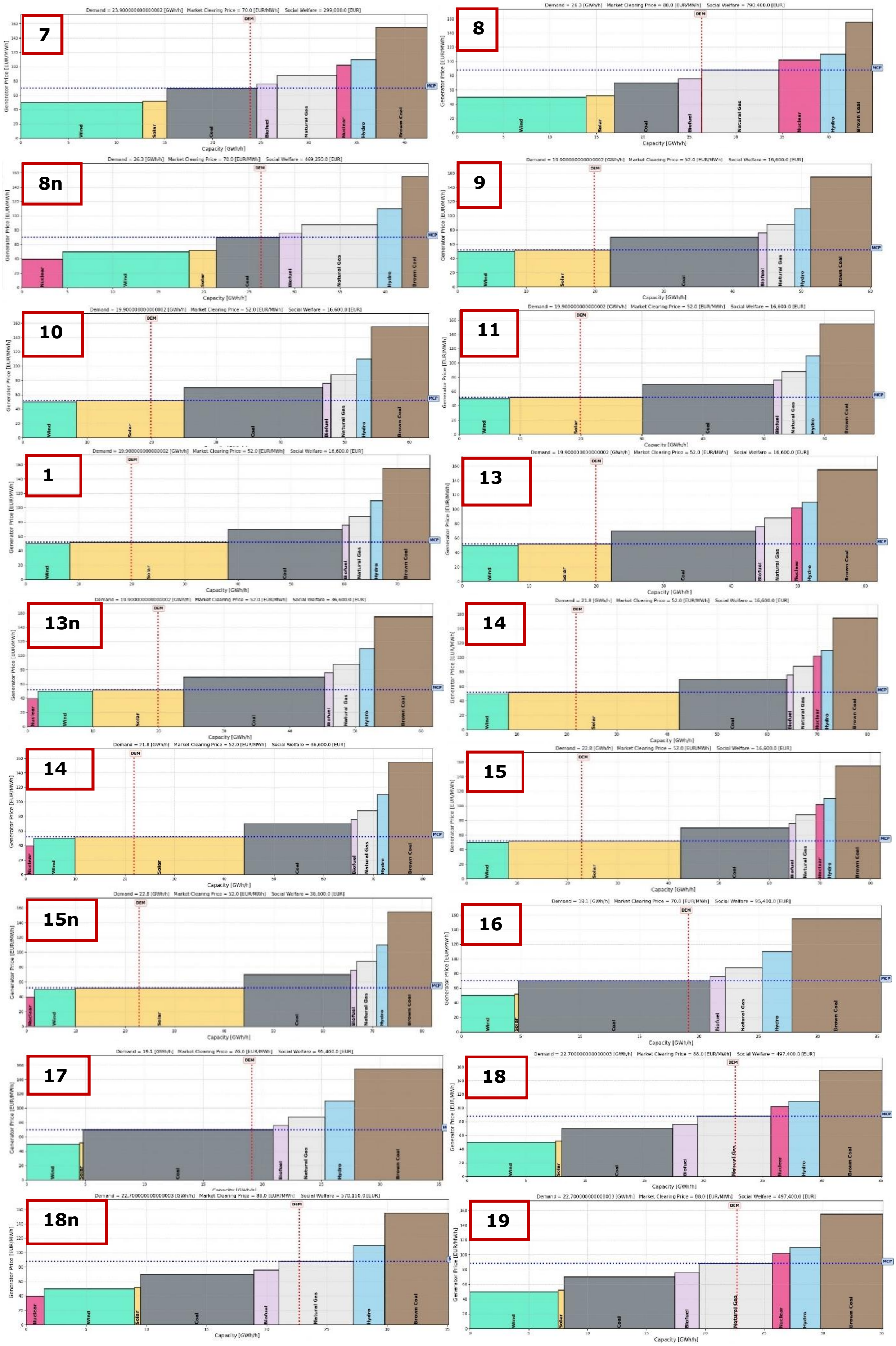
$$PRC_{emiss} = \; CO2_{emiss} * PRC_{ETS} \; [EUR] \qquad (5.3)$$

Where:

PRC_{emiss} – The cost of emission fees from a given technology $[EUR]$

PRC_{ETS} $[EUR]$ – cena jednostkowa pozwoleń na emisję CO_2; (tutaj 80.24 $\left[\frac{EUR}{Mg\ CO_2}\right]$; [46])

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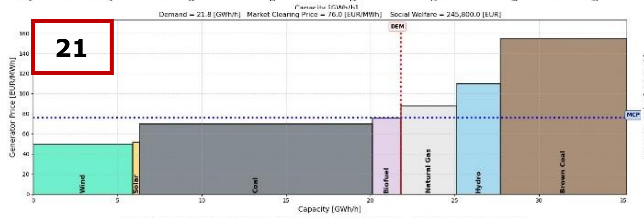

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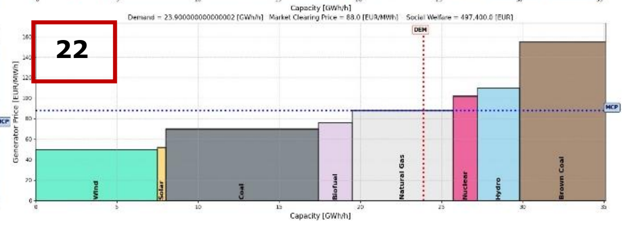

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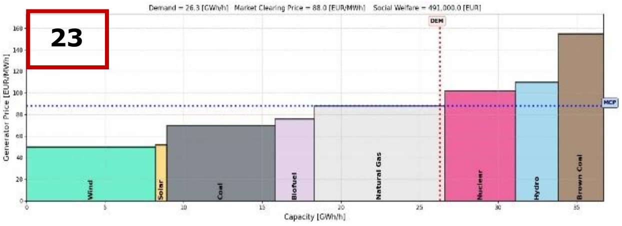

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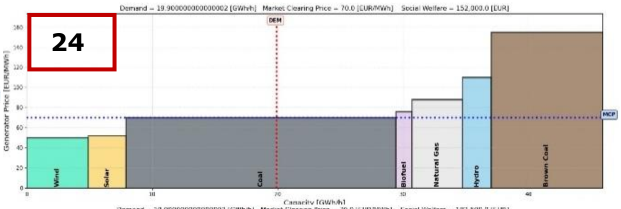

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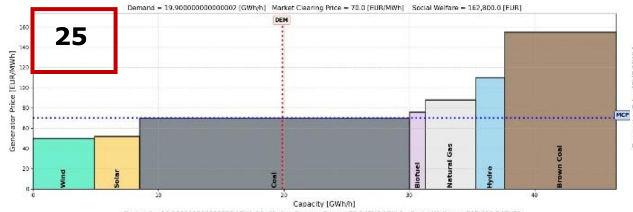

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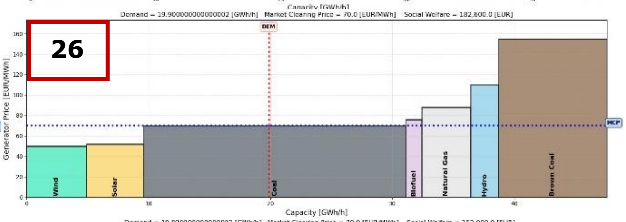

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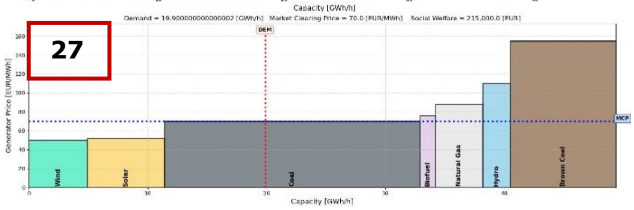

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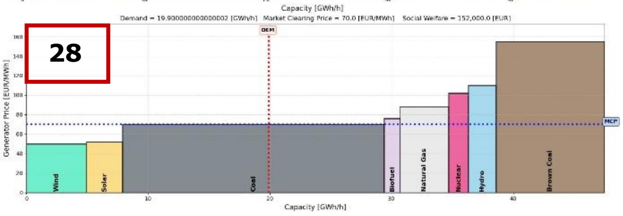

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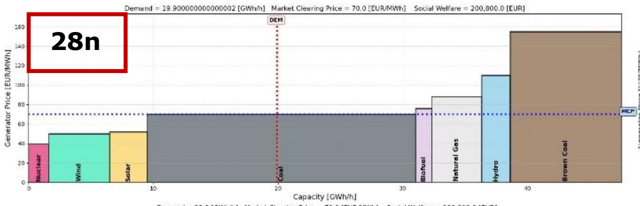

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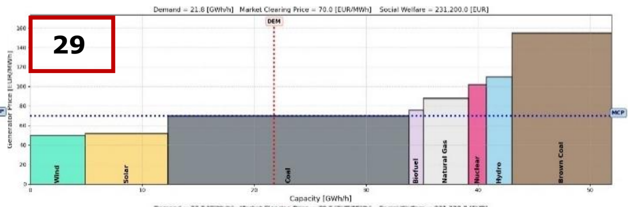

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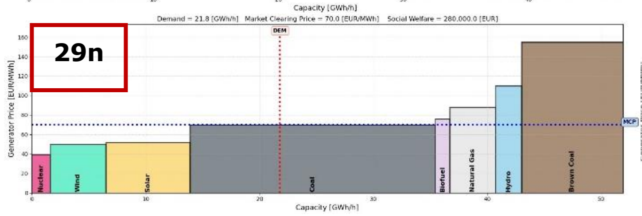

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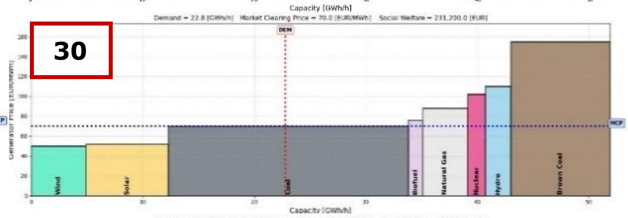

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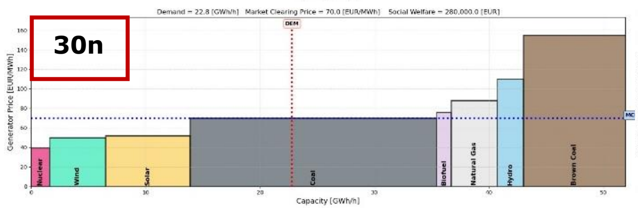

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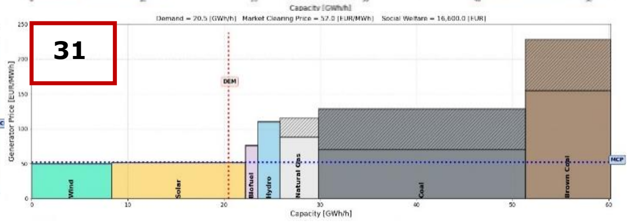

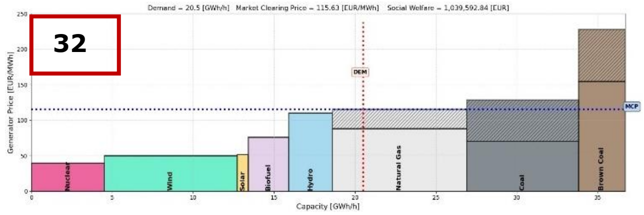
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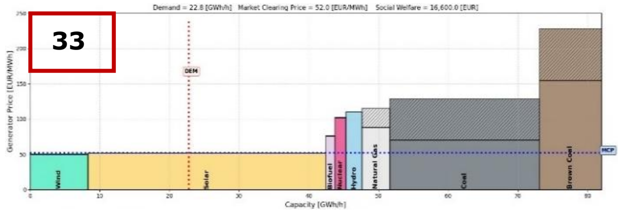
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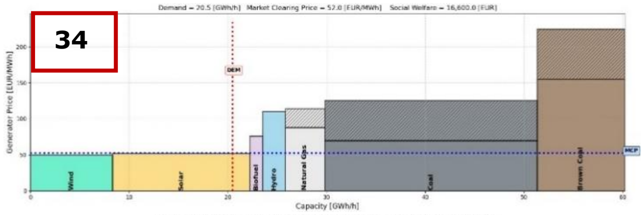
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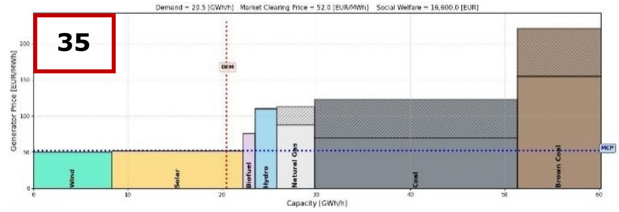
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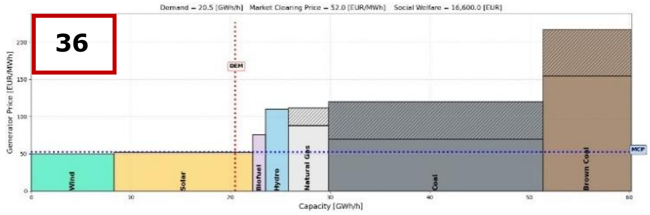
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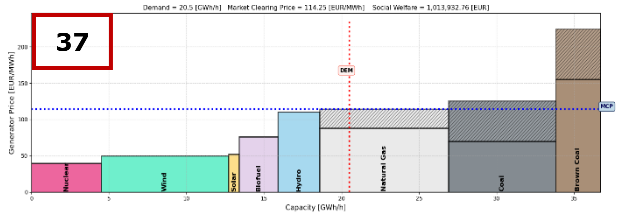
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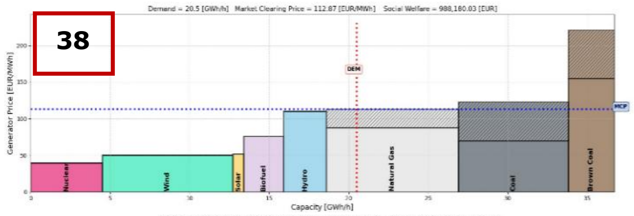
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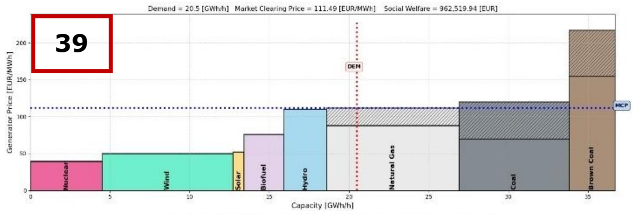
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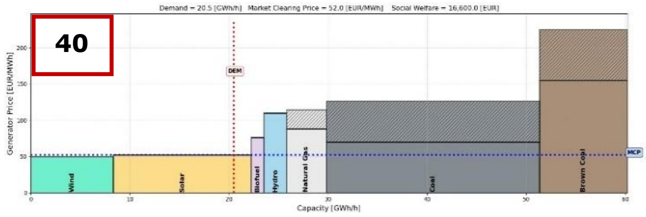
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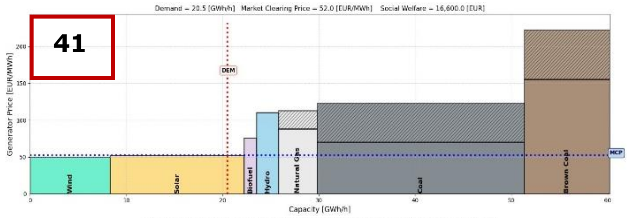
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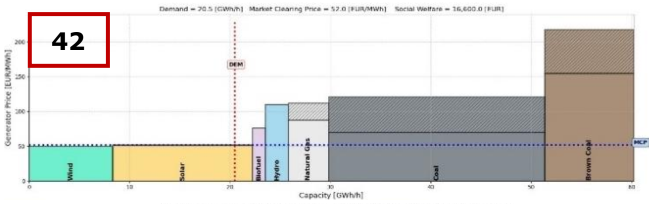
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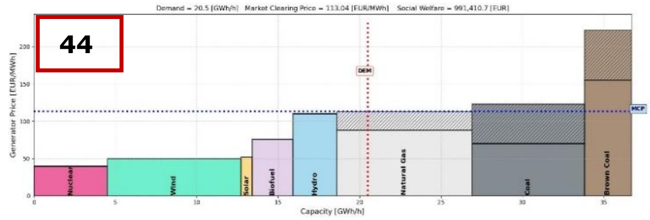
Demand = 20.5 [GWh/h] Market Clearing Price = 52.0 [EUR/MWh] Social Welfare = 16,600.0 [EUR]


43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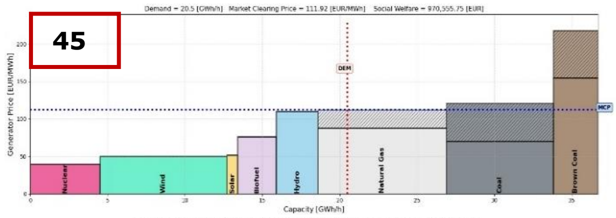
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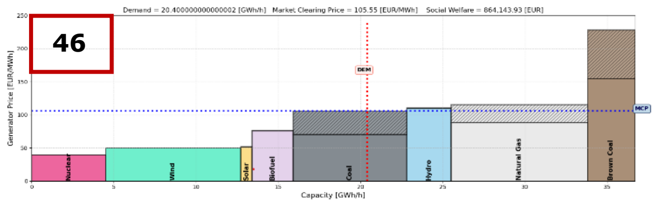
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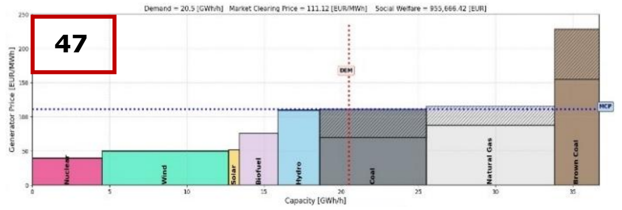
Demand = 20.400000000000002 [GWh/h] Market Clearing Price = 105.55 [EUR/MWh] Social Welfare = 864,143.93 [EUR]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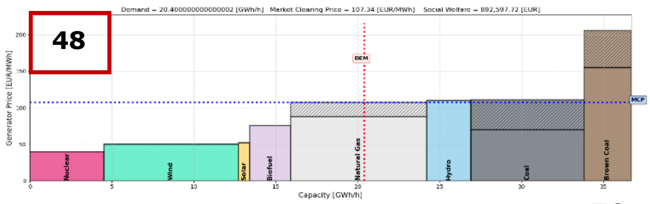
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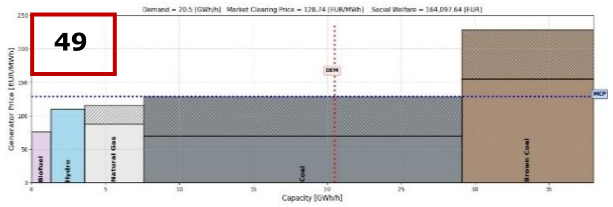
49

Figure 4.18 - results of parametric analyzes of the simulation merit order - variable parameters of power and energy prices from given technologies (cases with the letter "n" in the name mean that all simulation parameters are the same as in the case without this letter; a lower cost of generation from a nuclear power plant is assumed equal to PLN 39,5 [EUR/MWh] [47])

4.3.2 Brief explanation and summary of simulation parameter selection

In the simulation there are additional cases with the designation "n". These are cases that do not differ in any parameters from cases without this letter, however, they take into account a lower (calculated by experts the price of energy produced from nuclear power plants during its entire life cycle at 39.5 $\left[\frac{EUR}{MWh}\right]$). The base price of 102 [EUR/MWh] was chosen based on analysis of available data. As is well known, energy produced from nuclear power plants is the cheaper the longer the plant is in operation (since it requires large start-up investments which pay off over time and the fuel itself necessary for its operation is quite cheap) [55]. Thus, the assumption was made that in cases 1-30 two prices were considered each time. In cases 31-50, the rule of thumb was applied that for the years 2023-2033 the price of energy from nuclear will be higher (due to the fact that this will be the beginning of "repayment" of capital expenditures of the power plant) and in 2040 a lower price was assumed.

As for the selection and change of parameters for the following cases, the cases (1-15) are the most conservative. They represent the change in energy prices according to Poland's energy mix selected by experts. Then, due to the fact that in Poland we have a share of a large number of non-steering power plants, generation from wind and PV was statistically reduced in cases (16-30). Then the influence of the new factor of ETS fees for CO_2 emissions was added. This is illustrated by cases (31-33). Cases (34-39) illustrate what happens in the market when the price of fees fluctuates. Based on the first very rough observations, the parameters of the remaining 11 cases were selected according to the variables that are key to emissions price changes. This was done to study what influences CO_2 emission fees more: the efficiency of a power plant, the ETS price or the emission factor of a given technology. The last two cases (49-50) are purely theoretical and present a vision of the energy mix without non-steering power plants.

Now I would like to briefly describe the sets of assumptions made for each group of cases:

(1-4) - variants verifying basic forecasts for different years, according to data from strategic documents for Polish Energy [15], [45].

(6-8) - variants identical to cases (1-4) but a higher ceiling of projected demand was adopted [15]

(9) - variant for the current situation of Poland's energy mix in 2023

(10-12) - variants depicting Poland's energy mix today but the installed PV capacity was as projected for 2026 (for three different development ceilings) [47]

(13) - a variant for the current situation of Poland's energy mix in 2023, with the assumption that we already have a nuclear power plant available today to be commissioned in 2033

(14-15) - variant showing the situation in 2033 after the commissioning of the first unit of the planned nuclear power plant

(16-30) - variants with parameters identical to variants 1-15, but taking into account the real/possible generation of power from photovoltaics and wind (and not the entire available installed capacity, as can be done in the case of controlled power plants)

(31-33) - variants introducing ETS fees for CO_2 emissions for three selected years

(34-36) - variants showing the impact of changes in CO_2 emission factors for the base year 2023

(37-39) - variants showing the impact of changes in CO_2 emission factors for the year 2040

(40-42) - variants showing the impact of changes in the efficiency of coal-fired power plants for the base year 2023

(43-45) - variants showing the impact of changes in the efficiency of coal-fired power plants in 2040

(46) - variants showing the drastic increase in efficiency of coal-fired power plants for 2040

(47) - the variant of a drastic decrease in the emission factor of coal-fired power plants for 2040

(48) - variant of drastic decrease in ETS fees in 2040

(49-50) - the "no RES" variant for two selected years

4.3.3 Observations

Analyzing the simulation results switched in Figure 4.18, we can observe successively for sets of cases:

(1-4) - from year to year the demand for energy increases slightly; the installed capacity of coal and lignite decreases; the basis of the system is coal-fired power plants, as well as wind and solar; when in 2035 we will have a nuclear power plant nevertheless it will still be far in the merit order; assuming current energy prices in 2040 part of the power generation will be taken over by biomass power plants, but the price of energy will increase;

(5-8) - the trend in generation technologies will not change until 2040; natural gas will be an additional technology that will be able to sell its capacity in 2040, due to higher demand than assumed in the previous ones; the price of energy and social welfare will increase, as the technology of the marginal generating unit will have changed in 2040 and the price of energy will be higher than in the case of (5);

(9) - if we simulate the current state of installed capacity in Poland, purely theoretically, the entire demand for energy can be covered by non-steering PV and on-shore sources; conventional units would not be considered at all; energy would be very cheap and social-welfare would be very small;

(10-12) - assuming more photovoltaics in the Polish system, nothing changes with respect to case (9); we only have more power in non-controllable sources and the demand is still too low to use all of it;

(13-15) - assuming current prices for new nuclear power plants, if we had one now, it would not change anything in the system, given the parameters of this simulation case; however, if we counted the price of energy as an average price during the life cycle of the plant, it would be very low and competitive with virtually any other technology - in this case it would jump to the very top of the merit-order curve and record the highest excess profits; regardless of the years of simulation, the trend is identical even for increased energy demand; mainly wind and photovoltaic units and a nuclear power plant would be orchestrated to work;

(16-30) - after taking into account the relatively low generation from photovoltaics and wind turbines (compared to its installed capacity), the situation in the market changes dramatically; practically always until 2035 in order to make the price of energy the cheapest, the system proposes to dispose of wind, solar and mainly coal technologies, along with a large increase in the demand for energy are disposed of additionally first biomass units and then natural gas power plants; if we have a low-cost nuclear power plant in the system, it takes over part of the power that was previously generated by a natural gas power plant; in no case are hydroelectric or lignite power plants disposed of because they are too expensive; if in the case of (23) in 2040 energy consumption was slightly higher, the price of energy would be much higher and part of the power would be taken over by a nuclear power plant, even despite very high prices;

(31-33) - once ETS fees for CO_2 emissions are taken into account, the market situation changes somewhat; due to higher emission factors, coal ceases to be the primary controllable unit and becomes more expensive than biomass, hydroelectric, gas-fired and even expensive nuclear (until 2033); when we have a lot of photovoltaics and wind in the system, they are the ones proposed as the main generators; in 2040, on the other hand, when we take into account that we will never have 100% generation from solar panels the energy mix becomes much more diversified; the basic system is mainly based on nuclear power plant and windmills and supplemented by biomass, hydro and controllable low-emission gas power plants;

(34-39) - a decrease in emission factors in the range of 5-15[%] has little effect and for 2023 does not change energy prices; emission fees have made gas-fired power plants more expensive than hydropower plants, which was not the case in any of the previous cases;

(40-45) - if we raise the efficiency of all power plants by 5-15[%], none of the proportions between them will change relative to the previous cases; the pattern of prices will still be as follows: nuclear, wind, photovoltaic, biomass, hydro and natural gas;

(46) - a dramatic increase in the efficiency of coal-fired power plants by 30% causes it to move to the left in the merit order series and become a price-competitive source of energy for biomass, nuclear power and non-controlled sources; the system mandates that coal-fired power plants be put to work and the unit price of energy from this type of power plant is the marginal price and is 105.55 [EUR/MWh];

(47) - diametrane reduction of CO_2 emissions from coal-fired power plants by 30% caused them to shift to the left on the merit order graph (towards cheaper technologies); the price of coal-fired energy is cheaper than that of natural gas but higher than that of hydropower; the price of coal-fired energy is market clearing price and was 111.12 $\left[\frac{EUR}{MWh}\right]$ in this case;

(48) - if we reduce the ETS price by 30%, natural gas becomes the relatively cheap unit; the price of this unit is the market clearing price; the price of energy from coal practically equals the price of hydroelectric power plants, and none of these units will be put to work;

(49-50) - if we were to completely remove uncontrollable units from the system, the cheapest technologies would be biomass, hydroelectric power plants, natural gas, hard coal and, at the gray end, lignite; with the inclusion of cheap nuclear power in 2040, it would be the cheapest; in 2023, coal-fired power plants would be the basis of the system, and in 2040, natural gas and nuclear would hold that title;

4.4 Research - Application 2 "Simulation of the Balancing Market”

4.4.1 Case: excess power consumption (up-regulation)

Entry data

The data for the simulation is completely random, it is only intended to show the general trend in the balancing market.

Let's assume that in we have the following set of controllable generators (G_i), stochastic generators (Sg_i) and customers - with customers being buyers of energy in the market for distribution around the country or large end users (D_i) .

Table 4.15 - Generator data for simulation

Agent	Installed capacity [MW]
G_1	30
G_2	50
G_3	70

Source: own elaboration

Table 4.16 - Result of day ahead offers, real demand and deviation from the day ahead dispatch

Agent	Declared power/ consumption [MWh]	Purchase/ Sales [MWh]	Actual generation/ consumption [MWh]	Difference between Day Ahead and Balancing Market [MWh]
G_1	30	Sale	30	0
G_2	40	Sale	40	0
G_3	0	Sale	0	0
Sg_1	50	Sale	60	10
Sg_2	20	Sale	10	-10
D_1	60	Buying	55	-5
D_2	80	Buying	100	20
Market Clearing Price [EUR/MWh]			20	

Source: own elaboration

The data presented in Table 4.15 Table 4.16 shows that there are 3 controllable power plants with installed capacity of 30,50 and 70 [MW], 2 non-controllable power plants (wind or photovoltaic type) and 3 energy consumers (buyers). Demand for energy on the Day-ahead Market was 140 [MWh] and actual consumption on the current day was 155 [MWh].

In the day-ahead market, all G generators declared their power but only two of them sold it. Sg generators also declared their power but in fact one of them produced 10 [MWh] more and the other by the same amount below the level it declared. The D buyers' consumption was also not perfectly predicted for the day ahead market. One of them consumed 5 units less than it declared but the other as much as 20 more .

Differences between the declared and actual values of generation capacity and demand of non-controlled market participants are due to various reasons. In the case of RES power plants, all that is needed is inaccurate weather, a little sudden cloud cover or wind silence. In the case of may be a sudden need to turn on additional machinery in a production plant or a colder than expected day.

Balancing stage

To balance the system correctly, we need to count total net demand at the balancing market. This will be helped by the Formula 6.

$$P_{total_{net}} = \sum_{i=0}^{n} P_{D_{i_B}} - \sum_{i=0}^{n} P_{Sg_{i_B}} \; [MWh] \quad (6)$$

Where:

$P_{total_{net}}$ – total net demand at the balancing market [MWh]

$P_{D_{i_B}}$ – the actual energy demand of the following customers [MWh]

$P_{Sg_{i_B}}$ – power actually produced by the following non-controlled power plants [MWh]

For our case (data from Table 4.16) Total net demand is:

$$P_{total_{net}} = (100 + 55) - (60 + 10) = 85 \; [MWh]$$

If we know that non-controllable sources will generate 60 [MWh] + 10 [MWh] of power, we will be short 15 [MWh] in the balancing market].

If $P_{total_{net}} > P_{sheduled}$ then such a situation is called " excess consumption". In the balancing market, we can then only have offers to "sell energy" (because we want consumers to be able to buy the energy they are short of). Such offers are called "up-regulation".

At the next stage, controllable units submit offers for the disposal of their power to the balancing market. However, there are some rules "the offer of power generation on the balancing market can only be sold by controllable units that have previously participated in the Day Ahead Market and have not sold all their power there."

So, for example, a unit that participated in the previous day's auctions, but did not sell anything, as much as possible can offer itself on the balancing market. However, a controllable unit which did not take part in the Day Ahead phase cannot participate in the balancing phase.

Table 4.17 - Balancing market offers - dispatchable generators

Agent	Max available power [MW]	Proposed price [EUR/MWh]	Offer type
G_1	-	-	-
G_2	10	40	Up-regulation
G_3	60	50	Up-regulation

Source: own elaboration

Table 4.17 shows the bids of centrally dispatched power plants in the balancing market. In the case of "up-regulation", the task of selecting price and bids is as follows:

"we first select bids from the cheapest, slowly filling the demand and the price is set as the price of marginal generator".

Thus, in my case, sales and price are taken as in Table 4.18. Since the actual consumption exceeded by 15 [MWh] the previously planned one, in the balancing market this much energy must be bought.

Table 4.18 - Balancing market solve

Agent	Sold power [MWh]	Balancing price [EUR/MWh]
G_2	10 (fully dispatched)	50
G_3	5	50

Source: own elaboration

The cost results of the calculations are shown in Table 4.19.

Table 4.19 - Balancing market with excess production - results

Agent	Day-ahead market		Balancing market		Total [EUR]
	Cost [EUR/MWh]	Amount of energy to buy/ sell [MWh]	Cost [EUR/MWh]	Amount of energy to buy/ sell [MWh]	
G_1	600	30	0	0	600
G_2	800	40	400	10	1200
G_3	0	0	200	5	200
Sg_1	1200	60	400	10	1600
Sg_2	200	10	-400	10	-200
D_1	-1100	55	200	5	-900

D_2	-2000	100	-800	20	-2800
Price [EUR/MWh]	20		40		

Source: own elaboration

4.4.2 Case: excess production – down-regulation case

In this case, we will proceed exactly as in (a), except that there will be too much energy on the market.

Entry data

We assume that we have the same set of generators as in Table 4.15. We leave the situation the same way when it comes to declared consumption and generation in the Day Ahead market. We change the actual generation and consumption so as to induce an "excess production" situation in the market. Everything is shown in Table 4.20.

Table 4.20 -Result of day ahead offers, real demand and deviation from the day ahead dispatch

Agent	Declared power/ consumption [MWh]	Purchase/ Sales [MWh]	Actual generation/ consumption [MWh]	Difference between Day Ahead and Balancing Market [MWh]
G_1	30	Sale	30	0
G_2	40	Sale	40	0
G_3	0	Sale	0	0
Sg_1	50	Sale	50	0
Sg_2	20	Sale	30	10
D_1	60	Buying	50	-10
D_2	80	Buying	70	-10
Market Clearing Price [EUR/MWh]			20	

Source: own elaboration

Operational ganerators produce the same energy as before, while renewable sources generated more energy than declared, and consumers will consume less (it may be, for example, a warm, spring, sunny day in which workplaces will not need energy for heating and photovoltaics will have good conditions for energy generation.

Energy demand on the Day-Ahead Market was 140 [MWh] and actual consumption on the current day was 80 [MWh].

Balancing stage

To properly balance the system we need total net demand at the balancing market using Formula (6) and the data from Table 4.20.

$$P_{total_{net}} = (70 + 50) - (30 + 50) = 40\ [MWh]$$

If we know that non-controllable sources will generate 30 [MWh] + 50 [MWh] of power, we will have an excess of 40 [MWh] in the balancing market.

If $P_{total_{net}} < P_{sheduled}$ then such a situation is called " excess production". In the balancing market we can only have offers to "sell energy" in such a situation (because we want to get rid of it from the system). Such offers are called "down-regulation".

In this case, proposals cannot be made by G3 because it has not sold anything on the Day Ahead Market and cannot sell any more. G1, on the other hand, takes part despite the fact that he has already sold everything the day before. However, no one will prevent him from buying energy from others.

Table 4.21 shows the bids of centrally dispatched power plants in the balancing market. In the case of "up-regulation," the task of selecting prices and bids is as follows:

"we select bids from the most expensive first, slowly filling the demand and the price is set as the price of the cheapest (marginal) generator".

Table 4.21 - Balancing market offers - dispatchable generators

Agent	Max available power [MW]	Proposed price [EUR/MWh]	Offer type
G_1	40	10	Down-regulation
G_2	10	15	Down-regulation

G_3	0	0	-

Source: own elaboration

Thus, in my case, the sales and price are taken as in Table 4.22. Since the actual consumption exceeded by 40 [MWh] the previously planned one, in the balancing market this much energy must be sold.

Table 4.22 - Balancing market solve

Agent	Sold power [MWh]	Balancing price [EUR/MWh]
G_1	30	10
G_2	10 (fully dispatched)	10

Source: own elaboration

The cost results of the calculations are shown in Table 4.23.

Table 4.23 - Balancing market with excess production - results

Agent	Day-ahead market		Balancing market		Total
	Cost [EUR/MWh]	Amount of energy to buy/ sell [MWh]	Cost [EUR/MWh]	Amount of energy to buy/ sell [MWh]	
G_1	600	30	-300	30	300
G_2	800	40	-100	10	700
G_3	0	0	0	0	0
Sg_1	1000	50	0	0	1000
Sg_2	600	30	100	10	700
D_1	-1000	50	100	10	-900
D_2	-1400	70	100	10	-1300
Price [EUR/MWh]	20		10		

Source: own elaboration

4.5 Application 3 - "Computer game - simulation of the Day-Ahead Market”

The research and examples are mainly based on the following publication [48].

4.5.1 „Intersection of demand and supply profiles with excess energy to be to sell at the equilibrium point”

An example of a chart generated in the program can be found at Figure 4.19.

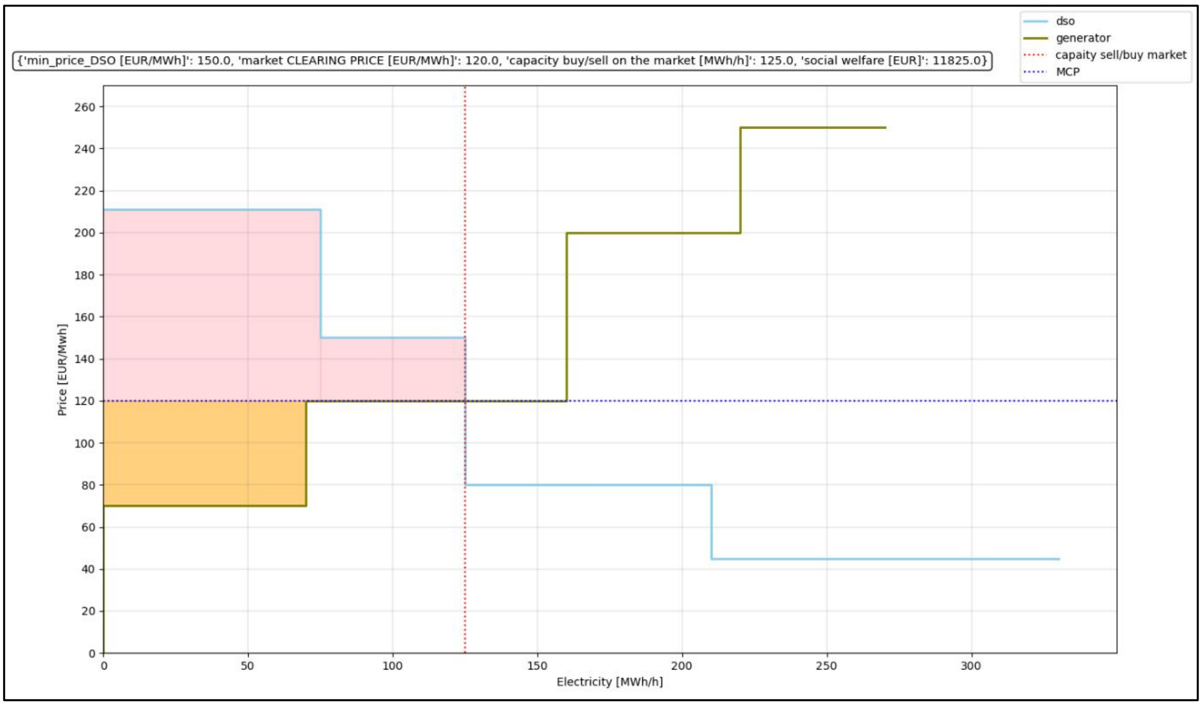

Figure 4.19 - An example of „Intersection of demand and supply profiles with excess energy to be to sell at the equilibrium point” – based on [60]

This is a classic market situation. Generators are arranged in ascending price order and buyers in descending order. The pink field is "consumer surplus," meaning that by using marginal-offer price selection, consumers will pay so much less for energy than they expected. We also have a "producer surplus," meaning producers, in turn, will get paid so much more than they expected. Both painted over create "social welfare." As we can see, two generators sold energy and two buyers got it. The market price was set as the price of the most expensive contracted unit.

Optimization in the program is to make the painted areas that symbolize social welfare as large as possible. Then producers earn the most and at the same time buyers save the most - the ideal equilibrium price is established.

4.5.2 Intersection of demand and supply profiles with the bearing of acquisition offers at the equilibrium point

Another interesting example is the case of Figure 4.20. Here, the first two generators sold their power completely, while the buyer symbolizing the second staircase acquired only part of the necessary power. Its price is again set as the price of the most expensive sales offer - the principle of lowest prices. On the

Polish exchange [60], on the other hand, the price of the lowest bid is respected, which in this case would be not 120 [EUR/MWh] but 150 [EUR/MWh].

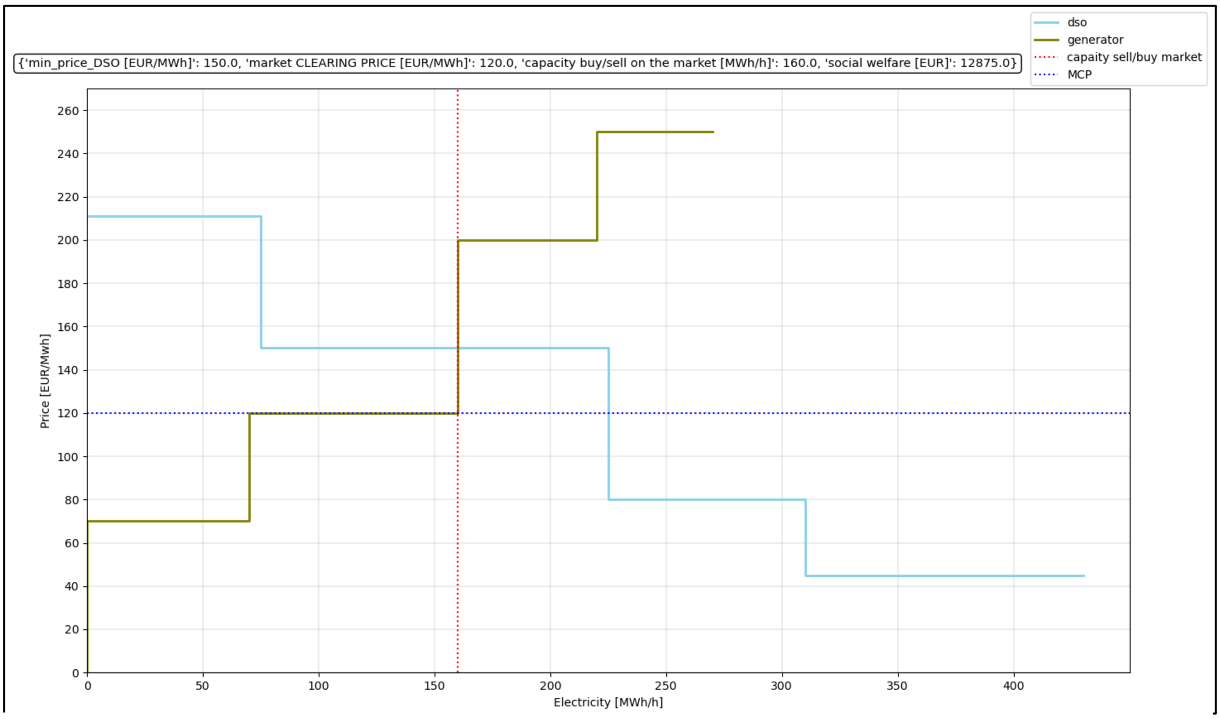

Figure 4.20 - An example of „intersection of demand and supply profiles with the bearing of acquisition offers at the equilibrium point" - based on [60]

4.5.3 Horizontal intersection of profiles of energy acquisition and sale offers

The case in Figure 4.21 does not happen often but is also worth considering. The last accepted sale offer is larger than the corresponding purchase offer. In this case, the seller does not sell his entire block only the corresponding part of it. Then we proportionally divide the sale offer according to the Equation (7) [48].

$$E_{s_i} = E_{O_i} \frac{E_Z}{E_o} \; [MWh] \tag{7}$$

Where:

E_{s_i} – the amount of energy sold by the generator "i" $[MWh]$

E_{O_i} – total energy offered for sale at "market clearing price" $[MWh]$

E_Z – part of the energy sold by the seller $[MWh]$

E_o – All the energy offered in the block by the vendor $[MWh]$

Of course, the final price in the Day-Ahead Market is in this the selling price of the most expensive generator and is equal to the cheapest purchase offer.

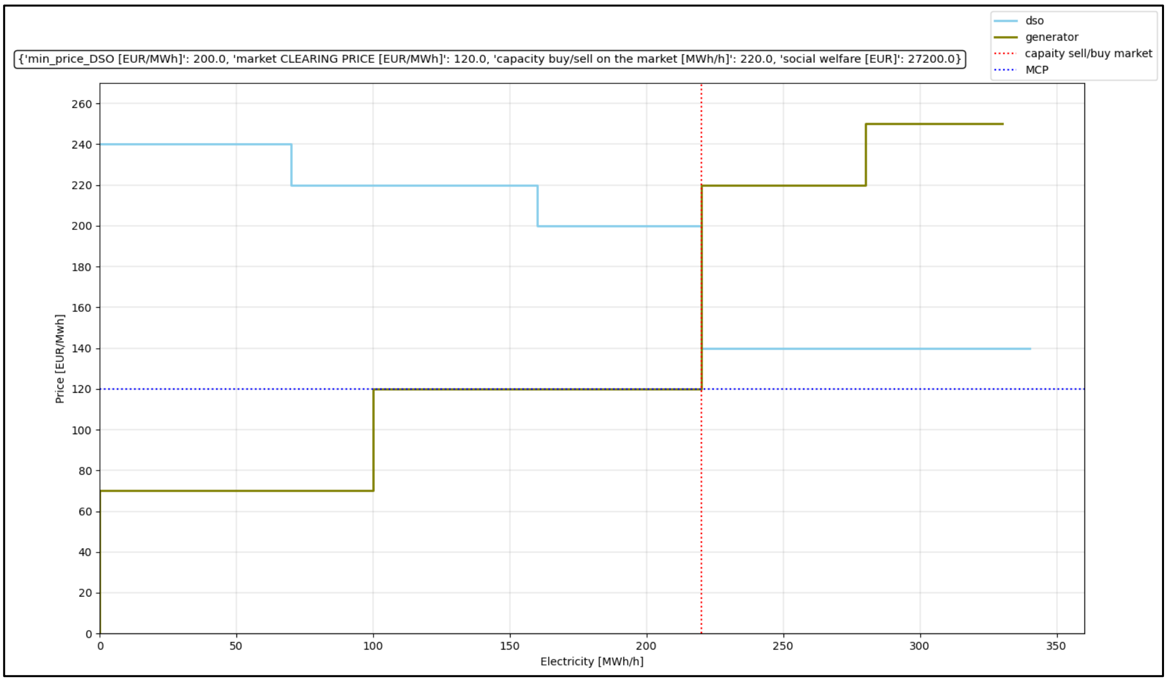

Figure 4.21 – An example of „horizontal intersection of profiles of energy acquisition and sale offers” - based on [48]

4.5.4 Vertical intersection of profiles of energy acquisition and sale offers

In this case, which is shown in Figure 4.22, the price applies to the price of the last accepted sales offer - the principle of the lowest price.

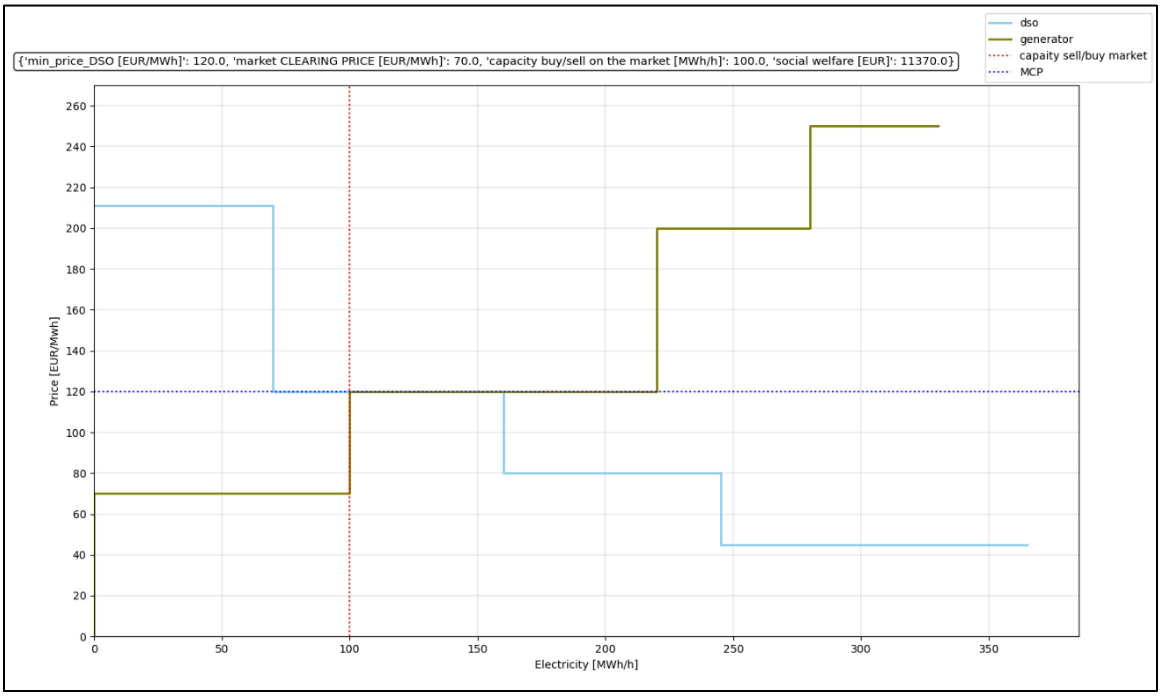

Figure 4.22 - An example of „vertical intersection of profiles of energy acquisition and sale offers” - based on [48]

In the power exchange in Poland, the equilibrium price is calculated according to formula (8). According to this formula, the market clearing price is the average price of the last accepted sales offer and the first rejected offer.

$$c_r = \frac{c(n)+c(n+1)}{2} \tag{8}$$

Where:

c_r – equilibrium price in the market (for me "market clearing price") $\left[\frac{EUR}{MWh}\right]$

$c_{(n)}$ – last sales offer accepted $\left[\frac{EUR}{MWh}\right]$

c_{n+1} – first unaccepted sale offer $\left[\frac{EUR}{MWh}\right]$

Then for our case, based on the data in Figure 4.22, c_r I can count the market clearing price according to the formula (8): [48]

$$c_r = \frac{120\left[\frac{EUR}{MWh}\right] + 220\left[\frac{EUR}{MWh}\right]}{2} = 170\left[\frac{EUR}{MWh}\right]$$

4.5.5 Excess of sales offers - no intersection of profiles

It may also happen that there are more offers to sell energy on the market than to buy it. Then we do not have a clear point of intersection of profiles. Such a situation is illustrated in Figure 4.23. Then the amount of energy traded is calculated as the sum of purchase offers and the final price is equal to the price of the last accepted sale offer.

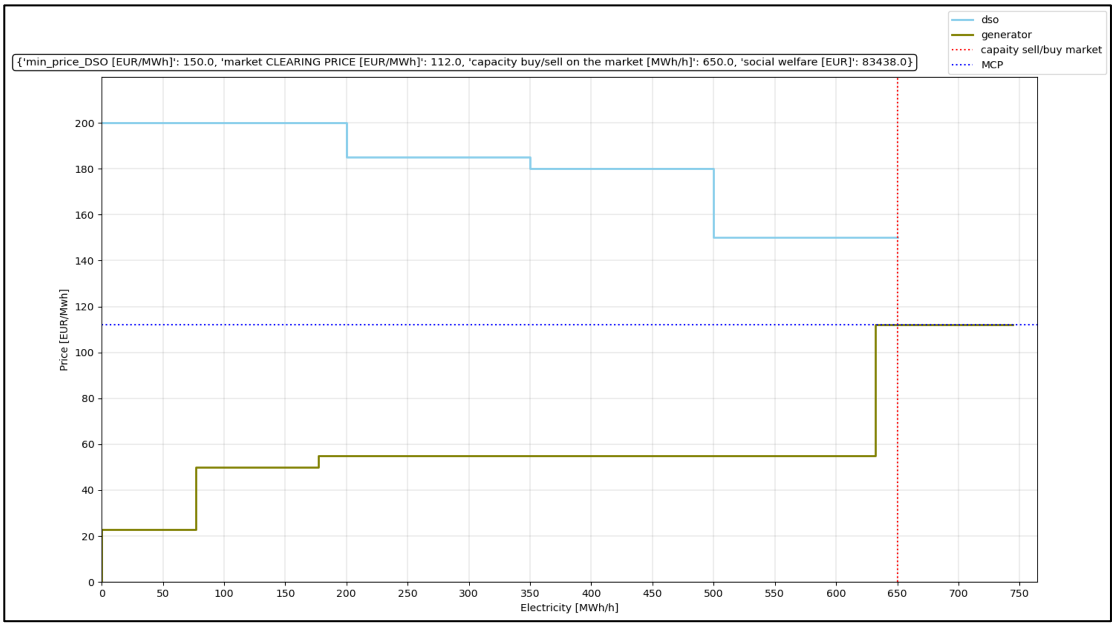

Figure 4.23 - An example of "Excess of sales offers - no intersection of profiles" - based on [48]

4.5.6 Excess of purchase offers – no intersection of profiles

The opposite situation to an excess of bids to sell is an excess of bids to buy energy volumes. Here I consider the case when the shape of the profiles does not allow them to be crossed. It is presented in Figure 4.24.

If we operate according to the general scheme of market clearing price is the price of the last accepted sales unit. If the entire volume is not purchased then this price is calculated from formula (7).

It is different on the Polish energy exchange. There, as the final price in such a situation, we assume the price of the last accepted purchase offer. In this case, on the Polish market clearing price would be 150 $\left[\frac{EUR}{MWh}\right]$ instead of 112 $\left[\frac{EUR}{MWh}\right]$ according to the general pricing scheme.

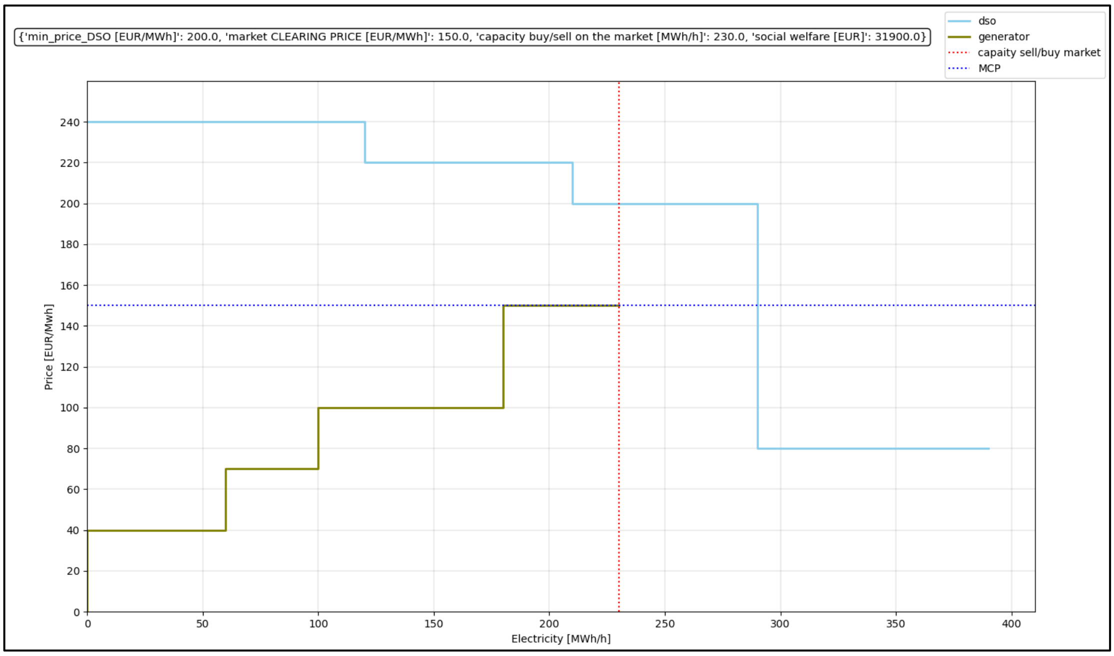

Figure 4.24 - An example of "Excess of purchase offers - no intersection of profiles" – based on [48]

4.5.7 No possibility of intersecting profiles - the case when the sum of the volumes of offers to buy and sell energy is the same

In such a case, as in Figure 4.25, all bids and offers made in the market are accepted. If we apply the minimum exchange price rule, then, as indicated in the chart, it is the price of the highest sale offer. In my case, it is 145 $\left[\frac{EUR}{MWh}\right]$.

In the case of the energy market in Poland, this will be the price of the lowest bid, i.e. according to the data on the chart, it will equal 165 $\left[\frac{EUR}{MWh}\right]$. [48]

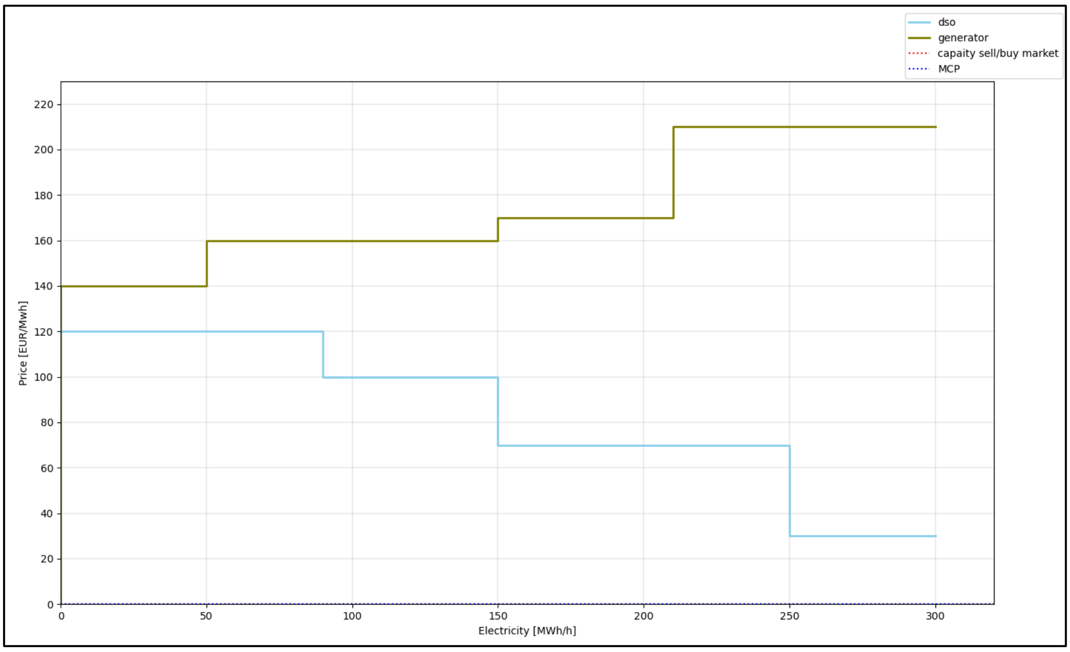

Figure 4.25 – An example of „equal volume of bids to buy and sell energy; no intersection of profiles" – based on [48]

4.5.8 Disparity in profiles of purchase and sale offers. Impossibility to determine the equilibrium price

This rare case, shown in Figure 4.26, occurs when the lowest generator price is higher than the highest purchase offer. Then the session closes with a volume of zero - no transactions are executed.

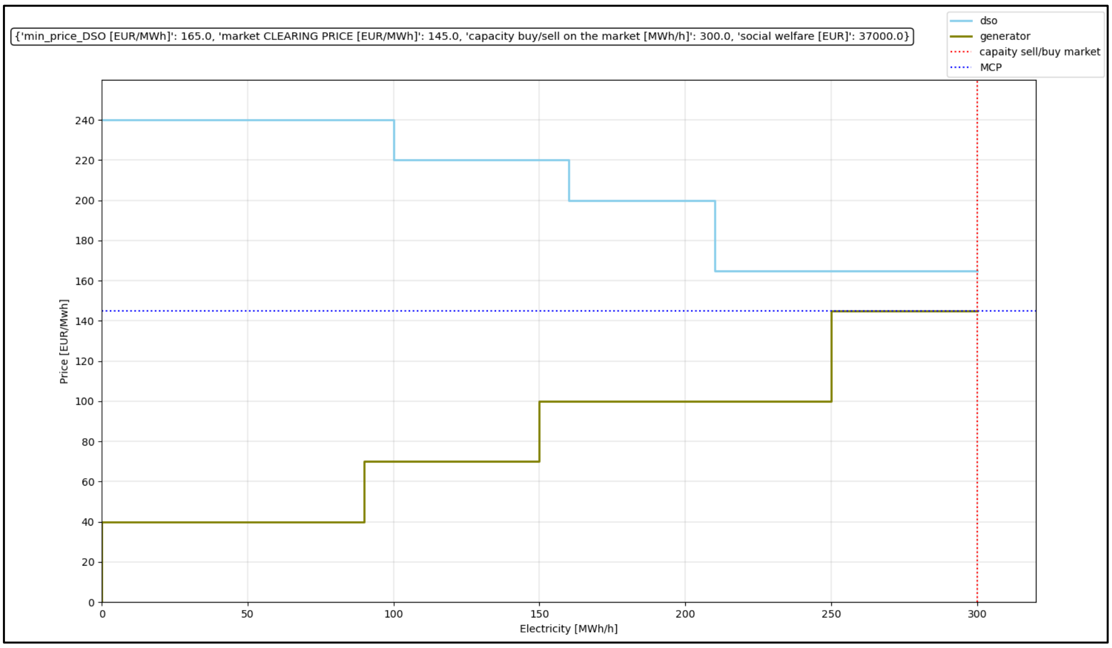

Figure 4.26 - An example of "disparity in profiles of purchase and sale offers. Impossibility to determine the equilibrium price" - based on [48]

5 Summary of results

5.1 Application 1 - "Merit Order Simulation”

- In the vast majority of variants, the cheapest energy comes, in turn, from wind, solar, and coal - these are the technologies our system would most like to use; the most common pattern is to maximize the use of RES technologies and select the rest of the energy from coal (this agrees, with the real-world generation statistics from each source shown in Table 4.8)
- The increase in energy demand that experts predict, even for 2040, does not exceed 5 [GW] per hour, which, as you can see from the charts, has little impact on the selection of units in the base cases (which include a lot of wind and photovoltaic power);
- Since it is practically impossible to obtain 100% of installed capacity from renewable sources, conversion factors according to formulas (3a) and (3b) were used, which allowed to select more realistic capacity values for these sources; the reduction in installed capacity for wind and pv has also brought other (more expensive) energy sources such as gas and biomass into play;
- In none of the cases discussed did the application indicate generation from lignite power plants; these plants have high CO_2 emissions and low efficiency;
- Reducing the price of energy from a nuclear power plant allowed it to jump ahead of the chart every time; so the application proposes that whenever a nuclear power plant came on the market and the unit cost of producing energy from it was an expert 39.5 [EUR/MWh] it should be maximized by the system;
- If the price of production from a nuclear power plant oscillated around the prices of the current application would not include it in the generation in any case;
- Currently, there is so much photovoltaic and wind in Poland that if a very sunny and very windy day came along, theoretically the entire installed capacity of these sources would exceed the demand for energy (all coal-fired power plants would have to be shut down); in practice, however, in good weather, we should still manage using only coal-fired power plants and the above-mentioned RES;

- If photovoltaic develops as predicted [52], it, together with wind power, could reach an installed capacity of more than twice the hourly energy demand as early as 2027;
- The cost of CO_2 emissions is influenced by the efficiency of the power plant, the cost of the ETS, and the emission factor of the technology; changing these parameters within 5-15% does not have much effect; changes of 30% have significant effects; it is definitely more cost-effective to increase the efficiency of the power plant than to reduce emissions from the technology;
- The greater the difference between the price of the marginal unit and the prices of cheaper units, the higher the social welfare;
- In the long term, nuclear power plant may be the cheapest technology and nowadays is the only one that can price-compete with photovoltaics and wind farms; generation costs at the very beginning of nuclear power plant operation are very high;
- Changes in emissions parameters definitely affect coal power prices more than natural gas prices;
- If there were no uncontrollable units in the system, the basis of generation would first be coal and, over the years, nuclear and natural gas plants;

5.2 Application 2 - "Balancing Market Simulation"

5.2.1 Excess consumption case

In my simulation, the classic generator will make the most money G_2 and stochastic S_{g1}. As can be seen from the results in Table 4.19, in the case of an energy shortage in the market, the best winners are those who sell the most on the Balancing Market, because the price of energy is always then lower than the day before. On the other hand, the worst offenders are those who underestimate their demand or declare the delivery of more power than can actually be generated (this applies to non-control units). Then they have to buy energy much more expensively.

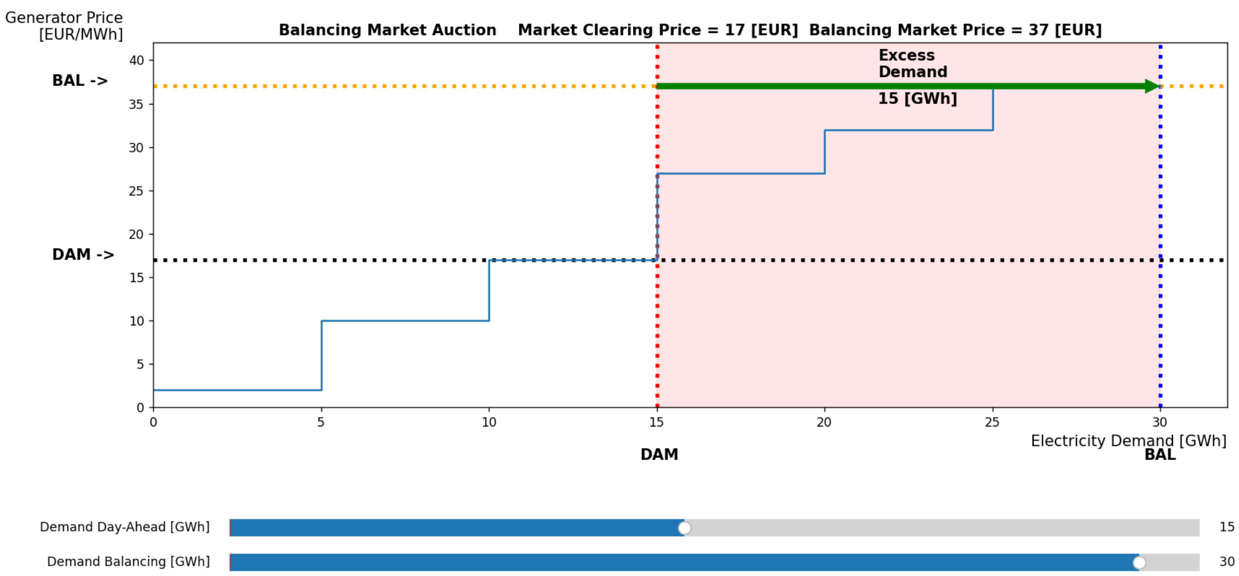

Figure 5.1 - The example of "up-regulation" and excess demand case

In the application I programmed, we can see what the situation on the balancing market looks like when too little demand was declared the day before (Figure 5.1). In this case (the data is completely different from the calculated case, I just want to present the rule here), all the units in the red box to the right of the "DAM" line are allocated. The price of the balancing market, on the other hand, has been set as the price of the last unit disposed, and as you can see in the chart, this must be much higher than in the Day ahead market.

5.2.2 Excess production case

In this simulation, the RES generator made the most money Sg_1 Which produced exactly as much energy as it declared. The second stochastic generator also earned quite a lot, however, he could have earned more if he had sold all the energy earlier at a higher price . The biggest loser is the customer who bought most of the energy on the Day-Ahead market, because now he has to resell part of it at a lower price than the purchase price. What is most profitable in this situation for consumers is to buy as much energy as possible on the balancing market because then it is the cheapest. An interesting thing is also happening with generators. In theory, we can say that G_1 and G_2 pomniejszyły swoje dochody o koszty zakupu energii z rynku bilansujacego. have reduced their income by the cost of buying energy from the balancing market. In fact, they still make money on it. Such power plants buy energy at a lower price and, instead of generating the corresponding amount from their resources, they resell it cheaper to customers. Thus, for every 1 [MW] they earn the difference in price between the markets. If a situation arose that a stochastic generator would produce less energy than it declared, such a situation would also be beneficial for it because it could buy it at a low price.

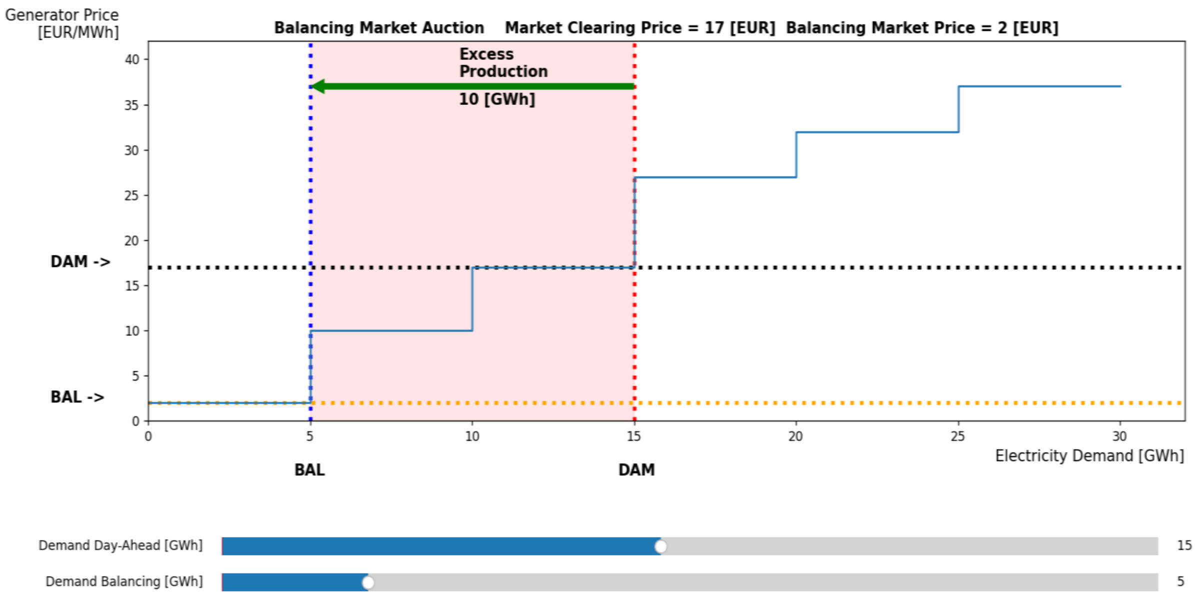

Figure 5.2 - The example of "up-regulation" and excess demand case

As before, a similar situation can be simulated in my application. In Figure 5.2, we see what happens when there is a surplus of energy in the market. The price in the Balancing Market has dropped. Everything follows the law of supply and demand. When supply is too high relative to demand, the price of a good must fall and may even be negative. Energy sales are made by units between the lines of primary and actual demand (that is, between the "DAM" and "BAL" lines). First the most expensive units are fully disposed of and then the cheaper ones. The price is set as the cheapest marginal unit. It can also happen that energy prices are negative, in a situation where there is, for example, a huge overproduction from renewable sources. Such a situation occurred this year in the Nordic countries and Germany. [58] At the same time, this was the result of an acute overproduction of energy from wind turbines. It is better then to give energy away even for free than to keep it in the grid, which can risk overloads and failures.

We can also see with this application, the effects of forecast errors on the price of energy. Moving the vertical line "DEM" to the left, we lower the price of energy - the situation when there is an oversupply in the market. Moving it to the right increases the price - a shortage of energy in the market. Thus, the greater the underestimation or overestimation of production and consumption in the energy market, the greater the losses and profits incurred by the relevant agents.

5.3 Application 3 - "Computer game - simulation Day Ahead Market”

Thanks to the application I created, we can simulate many situations that we can encounter in reality on the energy exchange. As my research has shown, the mutual alignment of buy and sell offers on the market is very important in the context of energy. When these graphs intersect we usually have two options:

- the price of the most expensive sale offer called the "lowest price rule" - the rule applied in general;
- the price of the lowest bid - the rule applied on the Polish energy exchange;

Already at this stage you can instinctively sense (after analyzing the examples I presented) that the lowest volume bid price (whenever we use it) will be higher than the price of the highest sales bid.

The horizontal intersection in the equilibrium price of buy and sell offers does not change anything in the energy price. It is always set at the level of the intersection. Only the volume of energy is not sold in full, but only as much as the buyer needs. For calculations, the formula (7) is used.

The price of energy, on the other hand, can be higher in the case of vertical intersection of bids. In the general case, the price is determined by the lowest price rule. In Poland, on the other hand, it is calculated according to formula (8) as the average of two bids for sale. Thus, the price of energy in this case depends not only on the offer of the final unit, but also on the offer that was not qualified. Thus the price of energy in Poland can be artificially much higher than in other countries applying the standard rule.

Another set of cases is when the curves on the graph do not intersect. If there is an oversupply in the market then there is no problem. The price is always set equal to the price of the marginal unit.

When we have more bids than sales in the market, the price of energy is shaped as in the case of vertical intersection. It can oscillate at the cost of the marginal unit and it can also be calculated according to Polish standards as the last offer to buy.

There is still a situation in which the supply and demand curves do not intersect, but both oscillate for exactly the same amount of energy. Then again, prices are generally set according to the "highest price principle" and in Poland at the level of the lowest bid. Again, this affects higher energy prices.

The last case considered was a situation where all sales prices are higher than any purchase offer. No bidding is then possible in the market and it closes with a volume sales balance of 0.

6 Conclusions

The price of energy is influenced by a great variety of factors, which I believe I have managed to present very well in the above work. The only thing we really have control over is how the price is set already directly in the market. All the rest of the factors are shaped by the basic laws of economics, the economic and political situation of countries and random events.

Already leaning directly to my research questions, such contingencies could be, for example, climate disasters. In fact, the temperature distribution in the country changes from year to year. This matters both in terms of energy consumption for air-conditioning rooms or heating (when it's very cold or hot the demand curve goes up) but also, for example, on the efficiency of photovoltaic panels. [49] The higher the temperature is than under standard STC conditions ($25℃$) the lower the efficiency of the installation. Climate change also affects the direction and strength of winds. This gives great uncertainty in estimating planned yields from onshore wind power plants. It would be much safer to use off-shore installations because winds at sea are more stable and stronger, but Poland still has to wait a while for its farms to come online.

So we can say that weather influences both sides of the market. It controls the demand and supply of energy and the transmission system operator has to fight all the time to balance the market. Based on the law of supply and demand and the results of my research, most often when we have a noon, sunny day we use less energy. Then there is an excess of it on the market and the price falls due to lack of demand because people are at work and school then (in extreme cases it can even be negative). When they return home in the evening, they need more energy and it becomes more expensive.

The above-described situation is also often combined with the need to dispatch conventional generating units when there is no yield from renewable technologies (non-controllable energy sources). This most often happens in the evenings. In Poland, energy storage is not yet developed and cheap enough to accumulate daytime overproduction and use it in the evening. Until recently, for owners of PV installations such storage was simply the transmission grid.

It is therefore necessary to support conventional units: coal, hydro or gas. But again, fossil fuels are much more expensive than RES, and subject to price fluctuations if only for political reasons. A perfect example is the increase in the price of natural gas and coal after Europe was cut off in February 2022. The lack of gas supply has not only increased its price but also the value of coal as a substitute. This naturally also increased energy prices which directly depend on the price of fuel (just as food prices depend on the cost of ingredients). In Poland, at one point these prices were frozen and coal had to be rationed to citizens. As my research has shown, if we had an operating nuclear power plant now, part of the demand could be met from its generation and Poland would then be much more energy and price independent. In addition, the more carbon-intensive the technology, the greater the cost to energy producers of paying for CO_2 emissions, and producers must add it to the price of the product. This paragraph can be summarized in such a way that energy prices are influenced by the shape of the country's energy mix, as well as by fuel prices which are constantly fluctuating.

Poland's energy mix already consists of almost 40% renewable sources, but nevertheless, controllable coal-fired power plants continue to be the backbone of the system. This is a key aspect of energy security and independence. Sometimes it so happens that the units at the base of the system fail. It is then necessary to orchestrate other, more expensive energy sources for them (on the merit order graph we move to the right). If the failure can be controlled when the unit is not loaded the Transmission System Operator can bail out by importing energy from a neighboring country. Otherwise, you either have to increase the power of other units or even wake them up for operation which is very costly. Again, such an unannounced event can destabilize the system and energy then will certainly be more expensive. Energy from RES is also much cheaper than that from conventional power plants. So photovoltaics or wind earn a lot in the merit order system and controllable power plants earn much less from it.

The most important conclusion I drew from my research is that the best way to avoid sudden fluctuations in energy prices is to balance the system well. The more balanced the supply and demand is, the more optimal energy price can be obtained by having the cheapest units available at all times. In Poland, the Balancing Market is used for this purpose. Any fluctuations in demand or generation that arise from the time the auction closes in the Day-Ahead Market until the time of delivery to consumers are flattened out in the Balancing Market. The operation of this armature is a strategic structure for national security. By constantly adjusting energy demand and supply, we as a country are able to avoid both blackouts and overloading the transmission grid. As my work has shown the Balancing Market also strongly influences energy prices. If we have an oversupply of energy on the grid at any given time, the price is set below the level of the Day-Ahead Market. This is a favorable situation for all market participants who have to buy energy because they have undervalued their offers. Then they have a lower price. These can be both stochastic generators whose weather forecasts have failed, but also DSOs. On the other hand, all those who overestimated their forecasts (produced more or consumed less than they anticipated) lose then. They are then forced to sell off the energy they previously bought or generated at a lower price than they acquired it. In this situation, conventional power plants can also make money, which buy energy at a low price and sell it to DSO at a higher one.

If we have too little energy in the market then automatically the price of energy goes up. The situation is exactly the opposite. It becomes a scarce commodity and then all those who are either able to produce it additionally (conventional power plants) or have too much of it make money.

In addition, we have different methods of setting the price still at the Day-Ahead Market stage. In Poland, these prices are often set at a higher level than in the rest of Europe, due to a different conversion system.

To summarize all the work, energy prices are affected by both fuel costs and the political, economic and climate situation. We can have different pricing patterns in the market and different generation technologies available. The more photovoltaic and on-shore units in the system, the harder it is to balance it. But the most important thing is really us - the consumers. They are the ones who decide the demand curve and again its appearance affects energy prices. Everything is really controlled by the basic laws of economics.

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8 Appendix

8.1 Appendix A – currency conversion rates

I tried to approach the issue of changing the value of money over time and currencies as fairly as possible. For this reason, in order to be able to compare different currencies with each other as accurately as possible, I converted them according to daily, daily, monthly (and when there was no other option) annual rates. Everything is shown in Table 7.1.

Table 8.1 - Currency conversion rates

Tag in text	Original currency	Post-conversion currency	Conversion rate	Aggregation rate	Year
a)	USD	EUR	0,951	annual	2019
a)	USD	EUR	0,846	annual	2022
b)	EUR	GBP	1,1878	half-yearly	01-06.2022
b)	EUR	GBP	1,1585	half-yearly	06-12.2022

Source: own elaboration based on [50], [51]

8.2 Appendix C – social-welfare counting programs

8.3 Social welfare counting program code in GAMS language

```
Sets
g generator set /g1*g4/
dso dso sets /d1*d4/;
Parameters
g_price(g) generator prices EUR per MW /g1 250,g2 200, g3 120, g4 70/
dso_price(dso) prices EUR per MW /d1 150, d2 45, d3 211, d4 80/
g_sell(g) power gen sell MW /g1 50, g2 60, g3 90, g4 70/
dso_buy(dso) power dso buy MW /d1 50, d2 120, d3 75, d4 85/;
Positive variables
veDSO(dso) power DSO buy
veGEN(g) power GEN sell;
free Variable
vObj;
Equations
eObj
eTransf
eGen(g)
eDso(dso);

eObj.. vObj=e=sum(dso,veDSO(dso)*dso_price(dso))-sum(g,veGEN(g)* g_price(g));
eTransf.. sum(dso, veDSO(dso))=e=sum(g, veGEN(g));
eGen(g).. veGEN(g)=l=g_sell(g);
eDso(dso).. veDSO(dso)=l= dso_buy(dso);
Model AGH /all/;
Solve AGH using LP maximizing vObj;
```

8.3.1 Social welfare counting program code in language Python

```
def soc_welf1(gen,dso,gprice,dsoprice,gsell,dsobuy):
    solvername=' cplex_direct'
    solverpath_exe = 'C:/glpk-4.65/w64/glpsol.exe'
    opt =SolverFactory(solvername,executable=solverpath_exe)

    #Defining the model
    model = pyo.ConcreteModel()
    model.g = pyo.Set(initialize = gen)
    model.d = pyo.Set(initialize = dso)
    g_n = len(gen)
    d_n = len(dso)

    G = model.g
    D = model.d

    #Defining decisinion variables
    model.power_DSO = pyo.Var(G, within = pyo.NonNegativeReals)
    model.power_GEN = pyo.Var(D, within = pyo.NonNegativeReals)
    model.g_price = pyo.Param(G, initialize = gprice)
    g_price = model.g_price
    model.dso_price = pyo.Param(D, initialize = dsoprice)
    dso_price = model.dso_price
    model.g_sell = pyo.Param(G, initialize = gsell)
    g_sell = model.g_sell
    model.dso_buy = pyo.Param(D, initialize = dsobuy)
    dso_buy = model.dso_buy

    #Objective function
    model.eObj = pyo.Objective(expr = sum(model.power_DSO[i]*dso_price[i] for i in
range(d_n))-sum(model.power_GEN[j]*g_price[j] for j in range(g_n)), sense = pyo.maximize)

    #Constrains
    model.eTransf = pyo.Constraint(expr = sum(model.power_DSO[i] for i in
range(d_n))==sum(model.power_GEN[j] for j in range(g_n)))
      # we add constraint when we have not sum in one side or constant
    model.max_gen_const = pyo.ConstraintList()
    model.max_gen_const.add(expr= model.power_GEN[i]<= g_sell[i]) for i in model.power_GEN
      # we add constraint when we have not sum in one side or constant
   model.max_dso_const = pyo.ConstraintList()
   model.max_gen_const.add(expr= model.power_DSO[i]<= dso_buy[i]) for i in model.power_DSO

    #SOLVER
    results = opt.solve(model) # solves and updates model
    print(results)

    #---PRINT RESULTS
    print("objective function= ", model.eObj())
return price_res_opt
```