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Master's Thesis

Simulation tools for a 100% renewable power market

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Abstract

This research focuses on the efficient integration of renewable energy sources into power systems through the application of an optimized economic dispatch model. The goal is to balance the beneficial aspects of renewable energy with the total costs of power system performance, using advanced management and planning tools. The study incorporates a detailed economic dispatch model, an investment model, and a commitment model, considering both the operational and investment costs. The primary objectives include developing a cost-effective strategy to meet the power demand and determining optimal generator capacities. The project aligns with Sustainable Development Goals 7 and 13, advocating for affordable, clean energy and climate action, respectively. The methodology involves a comprehensive review of the relevant literature, model development, real-world data collection, testing, and analysis of outcomes. The potential results could inform future energy planning and policy, supporting a transition to a more sustainable, low-carbon energy future.

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Chapter 1: Introduction

The world is currently going through a transition in the global energy landscape. A key factor in this change is the expansion of renewable energy sources, mostly wind and solar power, both of which have recently gone through significant technological progress and cost reductions. Renewable capacity additions in 2020, for example, expanded by more than 45% from 2019. An exceptional 90% rise in global wind capacity additions led the expansion. Also underpinning this record growth was the 23% expansion of new solar installations to almost 135 GW in 2020 [1]. Renewable sources have thus become a crucial element in global energy planning and policy as their greenhouse gas emissions are significantly lower, and due to their use, our dependence on fossil fuel sources is substantially reduced.

A primary challenge in this context is the integration of these variable renewable energy sources into the existing power systems. Unlike the traditional sources, renewables are variable in essence, meaning their generation potential is in large part dependent on environmental factors, such as weather patterns, time of day, and seasons. These changes pose major obstacles to stable and dependable power grid operation, necessitating innovative management and planning techniques adapted to this novel energy landscape.

A key concept when considering these tools is the economic dispatch. The fundamental goal of economic dispatch is to distribute power generation tasks in the most economical way possible to meet the demand.

Electricity is a unique commodity in that it cannot generally be stored at a large scale at a reasonable cost, so the entities that operate the transmission grid need to make plans and take actions to keep supply and demand matched in real-time. The process of dispatching generation plants to meet customer demands within a specified control footprint is variously known as "economic dispatch" or "optimal power flow." The terminology here is suggestive of the fact that generation plants are dispatched in such a way as to minimize the total cost of delivered electricity [2].

The economic dispatch algorithm is conceptually straightforward. It begins by turning on the generation source with the lowest marginal or operational costs. That generation source then increases its output until all load is met or the generation source hits its capacity constraint, whichever comes first. If the cheapest generation source hits its capacity constraint before all the demand is met, the second-cheapest generation source is turned on, and its power output increases until either it reaches its capacity constraint, or all the demand is met. The process continues by successively turning on more expensive generation sources until the entire load is served. It is important to realize that the economic dispatch algorithm does not consider any fixed costs of power plants - only those costs directly associated with plant operation [2].

The shift towards a higher share of renewable sources like wind and solar power makes the issue more complex. The generation capabilities of renewable energy sources vary depending on the time of day and season, making a thorough analysis of their specific constraints and characteristics essential for optimal operation.

This project seeks to address these challenges by developing an optimization model for economic dispatch and investment problems with a focus on renewable energy sources. The goal is to find an effective balance between the advantages offered by renewable energy and maintaining the total costs of power system performance as low as possible. The results of this research could further advance the efforts to transition to a sustainable energy system, ensuring a cleaner and more sustainable future.

1.1 Motivation

The motivation for this project arises from the growing importance of renewable energy sources in our global energy system. Energy is at the heart of the climate challenge – and key to the solution. A significant portion of the greenhouse gases that envelop the Earth and trap the sun’s heat is produced through energy generation, primarily by burning fossil fuels to produce electricity and heat [3]. Fossil fuels, such as coal, oil, and gas, are the predominant contributors to global climate change, accounting for over 75 percent of global greenhouse gas emissions and nearly 90 percent of all carbon dioxide emissions [3].

Renewable energy has become a cornerstone of global efforts to address pressing challenges such as climate change, energy security, and sustainable development. As the world moves towards a more sustainable, low-carbon energy future, the efficient and effective management of these renewable resources becomes an increasingly important aspect. According to the climate action plan of the United Nations, in order to circumvent the most severe impacts of climate change, emissions must be slashed by nearly half by 2030 and reach net-zero by 2050 [3]. Achieving this necessitates a shift away from our dependence on fossil fuels and a pivot towards alternative energy sources that are clean, accessible, affordable, sustainable, and reliable. Renewable energy sources, which are abundant and provided by natural elements like the sun and wind, are naturally replenished and release minimal to no greenhouse gases or pollutants into the atmosphere [3].

To summarize, this project is motivated by the need for the integration of renewable energy resources into our power systems. In a world striving for a sustainable energy future, it is essential that we effectively manage these resources. The proposed economic dispatch model helps to manage renewable energy integration. This model has the potential to make power systems operate more efficiently, reduce greenhouse gas emissions, and foster a more sustainable energy future.

1.2 Project Objectives

We begin our project by designing an economic dispatch model. Our primary objective in this step is to devise a system that can meet the energy demand of a specific area while minimizing costs. This model assigns electricity generation to different power sources in the most cost-effective way.

Our initial focus lies on a daily time scale. We examine the day thoroughly, studying the varying energy demands and prices throughout the day. By doing this, we aim to minimize the operational cost, while meeting the demand on a daily basis.

Then, we extend our model to incorporate an annual time scale. This broader perspective allows us to account for seasonal changes in energy demands and generation, which can have significant impacts on the optimal strategy.

The next step in our project is the integration of an investment model. While our economic dispatch model determines how best to distribute energy generation, the investment model is aimed at deciding the optimal capacities for different generators. This inclusion is vital because the decision about how much capacity to install will affect the dispatch decisions and vice versa.

Finally, we aim to achieve the ultimate goal of any energy project - meeting the energy demand at the lowest possible total cost. However, we take into account not just the operational costs, but also the investment costs associated with the capacity of different generators. By minimizing both these costs, we aim to develop a comprehensive, cost-effective strategy for energy dispatch that could help shape future sustainable energy systems.

1.3 Structure of the report

Chapter 2: State of the Art - In this part of the report, we're taking a look at the key methodologies and concepts currently being employed in the energy sector. It covers topics like the latest practices in economic dispatch and the crucial part investment models play in the sector. It also explores how the energy market works, what marginal costs mean, the present-day trends and challenges we're seeing in the industry, and how all of these fit into the broader goal of sustainable development.

Chapter 3: Methodology - The third chapter breaks down the models we used for this project. We start with the economic dispatch model, explaining its core principles, how we handle demand, the technology behind generation, our goals, and how we had to adjust for various constraints. We then scale up the model to look at it from an annual perspective, introducing changes in demand and technology, among other factors. Lastly, we present our investment model, taking a similar approach but with a focus on financial considerations.

Chapter 4: Results - In the fourth chapter, we present the results of our models. We start with the economic dispatch model, showing how much energy was dispatched, how much was curtailed, and how this compares to total demand. We also break down the cost of dispatch and explore the short-term marginal costs. This analysis is then repeated on an annual basis. Finally, we shift to the investment model, discussing investment generation capacities, dispatched energy, generation curtailments, costs, investment viability, as well as short-term and long-term marginal costs.

Chapter 5: Conclusion - The final chapter ties everything together. We take the findings from our models and analyses and discuss what they mean for the energy sector. We reflect on the implications of our work, discuss potential avenues for future research, and summarize our main conclusions.

Chapter 2: State of the Art

This chapter provides a concise look at current methodologies in economic dispatch, investment models, energy markets, and marginal costs. These key areas greatly influence the energy market and its strategic decision-making. We'll briefly outline modern trends, offering a clear understanding of the current landscape as a backdrop for our project.

2.1 Modern Approaches to Economic Dispatch

Economic dispatch is the process of allocating generation levels to the generating units in the mix, so that the system load may be supplied entirely and most economically [4]. The economic dispatch model represents an important challenge in the operation of power systems. A number of algorithms have been employed to optimize this economic dispatch problem. Notably, a modified bees algorithm implementing chaotic modeling principles was successfully applied on a physical model system of generators [5]. Other methods used to address the economic emission dispatch problem include Particle Swarm Optimization (PSO) [6] and neural networks [7]. With the shift towards renewable energy, we must include uncertainty and instability into economic dispatch models. This fact has produced the development of approaches that can handle those limitations.

2.2 The Role of Investment Models

In the energy sector, investment models hold great importance. They help in making pivotal decisions, especially with the liberalization of the market. These models guide us on how to expand generation, transmission, and distribution with all the given constraints. The selection and management of assets are crucial for the achievement of enterprises' objectives in the industrial sector. Among the company's tangible assets, those related to energy generation and management have special interest due to their impact on production costs and thermal comfort [8].

These models also help in examining the long-term impacts of policy decisions, changes in market structure, and technology innovation. The energy transition that is already taking place presents an opportunity for the industrial sector to adopt an active role in transforming the energy market, for example, becoming a prosumer [8]. Because of these models, we can make sure our energy projects are good for the environment and make financial sense. They're really important as we move toward using more green energy.

2.3 Market Mechanisms in the Energy Sector

The advent of liberalized markets has significantly altered the landscape of the energy sector. Traditionally, electricity sectors have developed and operated within strictly regulated frameworks in which most or all activities – from generation to transport to distribution – are handled within vertically integrated utilities. Often, there is great government involvement, both in ownership and in determining the framework [9]. In the late 1980s and early 1990s, a growing trend to liberalize traditionally public or regulated activities reached the electricity sector [9]. Inefficiencies in the traditional, vertically integrated utilities differed markedly from country to country, but substantial overcapacity in generation seemed to be a common characteristic [9]. As a result, the traditional cost-of-service pricing model evolved, giving way to more flexible pricing methods. Under pressure from competition, assets in the electricity sector are used more efficiently, thereby bringing real, long-term benefits to consumers [9]. Grasping these market dynamics is pivotal for devising effective strategies for economic dispatch and ensuring the financial robustness of power generation assets.

2.4 Understanding Marginal Costs

Marginal costs play a pivotal role in the economic dispatch of electricity. The marginal cost of electricity production at power system level is determined by the variable cost of the marginal generator, which is the one responding to changes in demand at a given time. In the long run, no cost, not even capital cost, is fixed. Consequently, the long-run marginal cost is found as the derivative of total costs, including investment, with respect to output. Short and long-run marginal costs may differ [10].

Understanding the dynamics of these costs is essential. A key assumption in the electricity sector is that, over the long term, marginal costs are flat, that is, they do not depend on the level of output. This is based in turn on the assumption that there are no economies of scale to be exploited, or that the availability of marginal technology or fuel is unlimited [10]. In essence, in modern energy markets, the price of electricity is set by the cost of producing one more unit of electrical energy. This way of pricing helps both suppliers and consumers make decisions that lead to lower costs with better usage of the available resources.

2.5 Alignment with Sustainable Development Goals

The work of this master thesis is aligned with the following sustainable development goals:

• SDG 7: Affordable and Clean Energy - By integrating renewable energy resources, the model contributes to the transition towards clean and sustainable energy systems [11].

• SDG 13: Climate Action - Reducing greenhouse gas emissions through the increased use of renewable energy resources helps mitigate climate change [12].

Chapter 3: Methodology

3.1 Economic dispatch model

3.1.1 Introduction

The Economic Dispatch Model is a crucial tool used in power systems operation. It is used to determine the most cost-effective way of power generation. The model seeks to produce power to meet the required demand, taking into account the associated operational costs and system constraints. The key objective of the model is to minimize the entire operational expense, which primarily comes from renewable energy sources. If these sources cannot fulfill the demand, fuel is used. Obviously, the model tries to prevent a power shortage, also known as 'energy not supplied' (ENS), given that the expenses of that occurring are substantially greater than any other energy production expenditures. In the first model, this occurs within a daily time frame. Overproduction can result in curtailments, meaning the excess generated energy is wasted or it needs to be stored, representing a significant opportunity cost. Technical restrictions, such as the power balance constraint and generation limits, must be respected. The economic dispatch model plays a vital role in ensuring economic efficiency in the operation of the power system.

3.1.2 Demand

Demand refers to the maximum amount of electrical power that is being consumed at a given time, as opposed to energy, which is the amount of power used over a period of time [13]. This concept is of pivotal importance in any power system, especially within the economic dispatch model. It signifies the required electricity consumption that needs to be met to ensure that the system can operate efficiently. Demand varies throughout the day and year due to factors such as industrial requirements and societal norms. It tends to peak in the morning before employees leave their homes for work and in the evening when they return home. This necessitates demand prediction and management to ensure that supply is always equal to demand. This is a core principle in our economic dispatch model.

Shifting our focus to our specific study, we are particularly concerned with meeting this demand primarily through renewable energy sources, as the project stems from the ambition to transition towards cleaner power systems, where the balance between supply and demand is maintained using renewable energy sources.

The entirety of the project was developed in Madrid, Spain. For these reasons, we saw it reasonable to take into account demand data for the country of Spain. Our demand data is sourced from the Spanish System Operator website, Red Eléctrica de España [14]. This national corporation is entrusted with the operation of the Spanish electricity system. It holds an extensive amount of data, such as power generation, demand, and transmission, which makes it a valuable resource for our study.

For the purposes of this study, we focus on the demand for one particular day - the 24th of April 2023 [15]. This date was selected as a representative of a typical day's demand in Spain.

In essence, our study aims to provide insights into how the demand in Spain can be met through renewable energy sources, using data from Red Eléctrica de España [14]. By analyzing the demand on a given day, we strive to propose an optimal dispatch of available renewable resources, thus fostering a transition towards more sustainable power systems.

3.1.3 Generation technologies

Generation technologies form a critical component of our energy system study. Within the framework of this study, we focused on two main generation technologies: solar and wind power. For the instances where renewable sources cannot fulfil the demand, we further used thermal power. Each technology carries unique characteristics, limitations, and capacities. Together they form a comprehensive energy generation network with the aim of meeting the given demand.

Solar power is an excellent source of renewable energy, especially in regions with high solar irradiation, as Spain definitely is. The country is one of the first countries to deploy large-scale solar photovoltaics and is the world leader in concentrated solar power (CSP) production. In 2022, the cumulative total solar power installed was 19.5 GW, which accounted for 11.5% of total electricity generation in Spain, up from 2.4% in 2010 and less than 0.1% in 2000 [16].

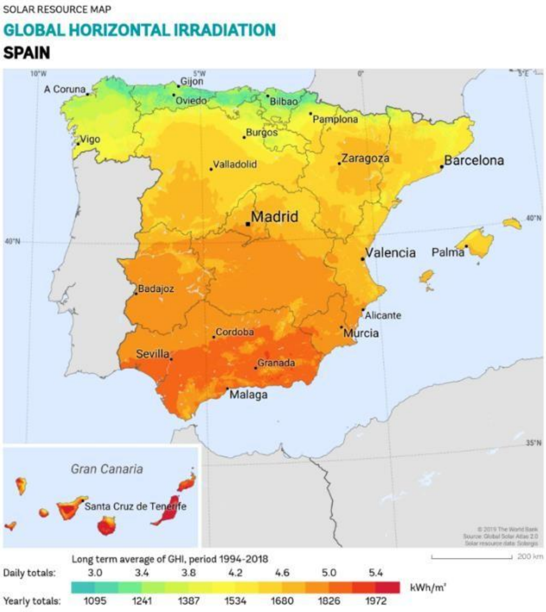

Figure 1: Spain irradiation map

The image reveals Spain's diverse solar potential. The southern regions, with their abundant solar irradiation, exhibit the highest potential. Central Spain follows closely. The northern areas do not display such a high solar potential due to their climatic limitations. Overall, the country has a remarkable capability for solar energy utilization, which makes it an ideal candidate for the purposes of this study.

The country is firmly establishing itself as a leader in renewable energy within Europe. According to a study by Rystad Energy, [17] the country is on track to generate more than half of its power from renewable sources this year, the first of the top five European countries by power demand to accomplish this feat. It will reach this significant decarbonization milestone this year, beating France, Germany, Italy and the UK to this record [17].

The nation's cumulative installed capacity of solar photovoltaics is anticipated to reach 27,4GW in 2023, a significant increase from 20,5GW in 2022. Therefore, the installed capacity of solar and wind in Spain will be 58GW this year [18].

Figure 2: Francisco Pizarro PV plant in Extremadura, Spain

Spain is not only increasing its renewable capacity but is also home to the largest single solar PV plant in Europe. The Francisco Pizarro project, commissioned in 2022 by the Iberdrola Group [19], has installed capacity of 590 MW. The plant is located in Cáceres, a region of Extremadura. It provides clean energy to 334.400 homes a year and will become the largest photovoltaic plant in Europe. By doing so it will avoid the emission into the atmosphere of 150.000 tones of CO_2 per year and reducing the carbon footprint.

Wind power is another crucial component of Spain’s renewable energy mix. The country has been a pioneer in wind energy development since the 1990s and is currently the fifth-largest producer of wind power globally [20].

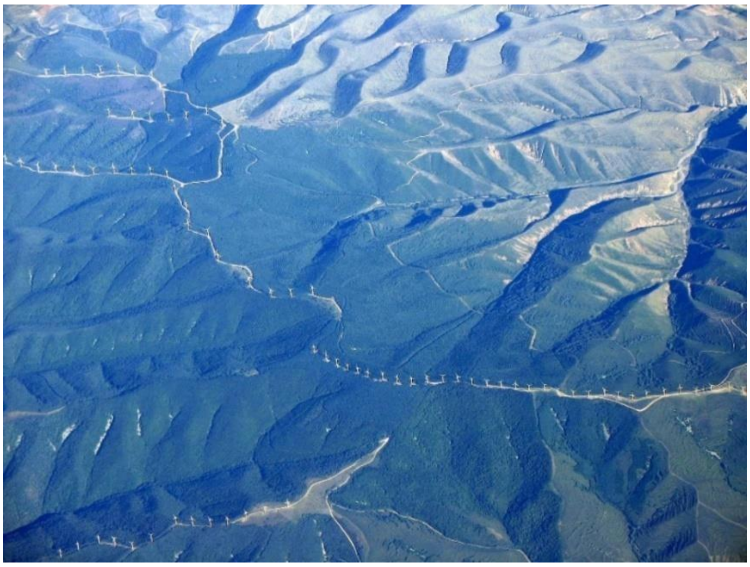

Figure 3: Air view of a wind power plantation in Sierra de Gredos, Spain

The country's terrain is particularly well suited for harnessing wind power. Certain regions exhibit exceptional wind potential. The northwestern region of Galicia is a major contributor to Spain's wind power generation due to its coastal location with consistent wind conditions. Likewise, Castilla y León in the northwest and Andalusia in the south also host a substantial number of wind power plants due to favorable wind conditions and large open spaces. According to the IEA Wind TCP 2021 Annual Report, the Spanish wind sector installed 842.61 MW of offshore wind power during 2021 and aims to have up to 3 GW of offshore wind power installed by 2030 [21]. However, the broader goal for wind capacity in Spain, as outlined in the Integrated Plan for Climate and Energy, is much more ambitious, setting a target of 62 GW by 2030 [22].

Due to their variable and inconsistent nature, there are periods where wind and solar energy sources cannot fulfill the demand. For the purposes of this study, we resorted to thermal generation in those periods. These generators, unlike their renewable counterparts, are able to provide a stable energy generation, thus their output can be adjusted as we please. There are downsides to this however, as their operating costs and greenhouse gas emissions position them as a less preferred option in the framework of our study.

Lastly, when even the thermal generators fail to meet the demand, we resort to the concept of 'Energy Not Supplied' (ENS). ENS means the quantity of energy that the generators in our system are unable to meet due to constraints. This can lead to load shedding or blackouts. These scenarios negatively affect service quality and lead to significant economic costs. In every power distribution system, the objective is to eliminate ENS and ensure consistent supply and maintain grid stability.

The production profiles for solar and wind energy technologies were derived from the same source as our demand data - the Spanish website, Red Eléctrica de España [13]. These profiles reflect the inherent variability in these renewable resources and play a vital role in our dispatch decisions.

3.1.4 Objective function

In the context of our project, the objective function represents the optimization objective we intend to fulfill. The goal is to minimize the cost of the dispatched electrical energy. This is the function that we strive to optimize in the decision-making process. It represents a fundamental step in the mission of our project, which is minimizing the cost of the energy production, while also meeting the demand.

The structure of the function tells us about the interaction of different components in the system.

$$\sum_t \left(\sum_g \left(C_W \times v_{W(g,t)} + C_{PV} \times v_{PV(g,t)} + \left(C_{THa} + C_{THb} \times v_{th(g,t)} + C_{THc} \times \left(v_{th(g,t)} \right)^2 \right) \right) + C_{ENS} \times v_{ens(t)} \right)$$

Equation 1: Economic dispatch objective function

This function calculates the sum of the costs of energy generation from each type of generator (wind, PV, thermal) and the cost of any energy not supplied (ENS), across all time periods.

The equation uses the following terms to calculate the total sum of the generation cost:

• *CW* represents the cost per unit of energy from wind generation, and *vW(g, t)* is the volume of energy produced by wind generator during each time step. The multiplication of the parameter with the variable represents the cost of energy generated by the wind turbines during the course of the day.

• *CPV* is the cost per unit of energy from PV generation, and *vPV(g, t)* is the volume of energy produced by the PV generator. The multiplication of the two represents the cost of energy generated by photovoltaic generators during the span of 24 hours.

• $CTa + CTb \times vt(g, t) + CTc \times (vt(g, t))^2$: This term calculates the cost of energy produced by thermal generators. It represents a quadratic cost function, signifying that the cost of operation increases non-linearly with the volume of energy produced. Here, *CTa, CTb*, and *CTc* are cost coefficients, and *vt(g, t)* is the volume of energy produced by thermal generator during each time interval.

• *CENS × vENS(t):* Lastly, this term covers the cost of any energy not supplied (ENS). *CENS* is the cost associated with each unit of unserved energy, and *vENS(t)* is the volume of energy not supplied in each interval.

3.1.5 Power balance constraint

Understanding the role of constraints in the economic dispatch model is crucial. Constraints define the operational boundaries in our power system. The first constraint to consider in our case is the power balance constraint. This constraint necessitates that, at all times, the total power produced by all generators in the system along with ENS must equal the total demand.

The power balance constraint, as stated in the equation, can be represented as follows:

$$\sum_{g}\left(Vpv_{(g,t)} + Vw_{(g,t)} + Vth_{(g,t)} \right) + Vens_{(t)} = QDh.norm_{(t)} \times QD$$

Equation 2: Economic dispatch power balance constraint

In this equation, the sum of energy produced by all generators and ENS must equal *QDh.norm(t) × QD*, where *QDh.norm(t)* is the normalized demand, and *QD* is the demand magnitude, by which the normalized profile gets multiplied.

The power balance constraint plays a key role in our economic dispatch model, primarily ensuring system reliability. Its central principle is maintaining an equilibrium between supply and demand. This balance is essential in power systems, where the large-scale storage of electricity is not typically feasible, and therefore, the power produced must be consumed in real-time.

Furthermore, this constraint refines our objective function, making it more realistic. The objective function aims to minimize power generation costs, and the power balance constraint sets the physical boundaries for this cost optimization. It prevents solutions that are theoretically possible but not feasible in practice, avoiding disruptions to the power supply-demand balance.

3.1.6 Generator constraints

Each energy source in a grid has its own unique characteristics and limitations. These parameters are crucial to consider when optimizing the dispatch of power generation. By acknowledging and integrating these distinct characteristics into the model, we can ensure that the operational decisions made are not just economically sound but also physically feasible.

$$v_{W(g,t)} \leq Q_{Wh.norm(g,t)} \times Q_{W}$$

Equation 3: Wind generator constraint

First we take into consideration the constraint of the wind generator. The equation ensures that energy produced from each wind generator *vW(g, t)* at any given time does not exceed the available capacity that the wind turbines can offer. *QWh.norm(g,t)* represents the normalized profile of wind generation, while *QD* stands for the maximum capacity of the wind power generator. By imposing this constraint, the model makes sure that the solution does not assume generation values that are in reality unattainable.

$$v_{PV(g,t)} \leq Q_{PVh.norm(g,t)} \times Q_{PV}$$

Equation 4: Solar generator constraint

The second generator constraint pertains to solar energy generation. The produced energy from each PV generator *vPV(g, t)* must not exceed its available capacity. The term *QPVh.norm(g,t)* represents the normalized solar power, and *QPV* represents the maximum capacity of the PV generator. By multiplying the normalized solar values with the maximum capacity and imposing that the product is always greater or equal to the produced energy, we ensure that the model keeps the produced energy within the practical limits.

$$v_{TH(g,t)} \leq Q_{THh.norm(g,t)} \times Q_{TH}$$

Equation 5: Thermal generator constraint

The third generator constraint relates to thermal power generation. It is constructed much the same way as the previous two equations, by ensuring that the power output from the thermal generators *vTH(g, t)* doesn't surpass its maximum generation capacity. Unlike renewable resources, thermal power generation is not dependent on weather conditions. It is rather limited by the generator's capacity and efficiency.

These 3 constraints work together to ensure the feasibility of the model's results. By not breaching these restrictions of wind, solar, and thermal generation, the constraints ensure that the project's goal is reached, which is to say that an optimal dispatch schedule that is not only economically efficient but also realistic is implemented.

3.1.7 Input parameters

The input data for our economic dispatch model primarily consists of power generator capacities, demand and costs. The key components of our model and their respective details are elaborated below:

• **Number of Generators and their Types:** Our study focuses on three types of power generators - wind, solar PV, and thermal. These three sources form the pillars of our energy generation system. It also offers a comprehensive view of the dynamic between non-renewable and renewable energy sources.

• **Number of Loads:** Our model contains one load point, representing the energy demand of Spain on 24th of April, 2023. Although power systems may serve multiple demand points, our choice of one load point simplifies the model while covering the overall energy requirement.

• **Time Horizon and Periods:** The study operates over a 24-hour period, divided into 12 periods per hour. Each period thus represents a 5-minute interval, resulting in a total of 288 periods. This high granularity ensures that our model accurately captures the variations in renewable power generation and demand within the day.

• **Generation Capacities and Costs:** Each generator type in our model has a defined maximum generation capacity. In this case study, we determined the total technology capacities of 30 GW for wind and solar, and 5 GW for thermal. Furthermore, we defined the variable costs associated with each type of generator. 5 €/MWh for solar and 10 €/MWh for wind generation. For the thermal generator, the costs are defined using a quadratic cost function of $(900 + 45x + 0{,}01\ x^2)$ €/MWh. This formulation reflects the real-world operation of thermal generators, where the operational cost increases non-linearly with the output.

• **Energy Not Supplied Cost:** This parameter represents the cost associated with failing to supply the demand. It reflects the substantial economic impact and potential business disruptions that come from unfulfilled power demands, in our case 7880 €/MWh.

• **Demand Data:** The load demand data was sourced from Red Eléctrica de España [14], representing the energy demand in Spain on 24th April 2023. The data was normalized and visualized in a plot for clearer understanding.

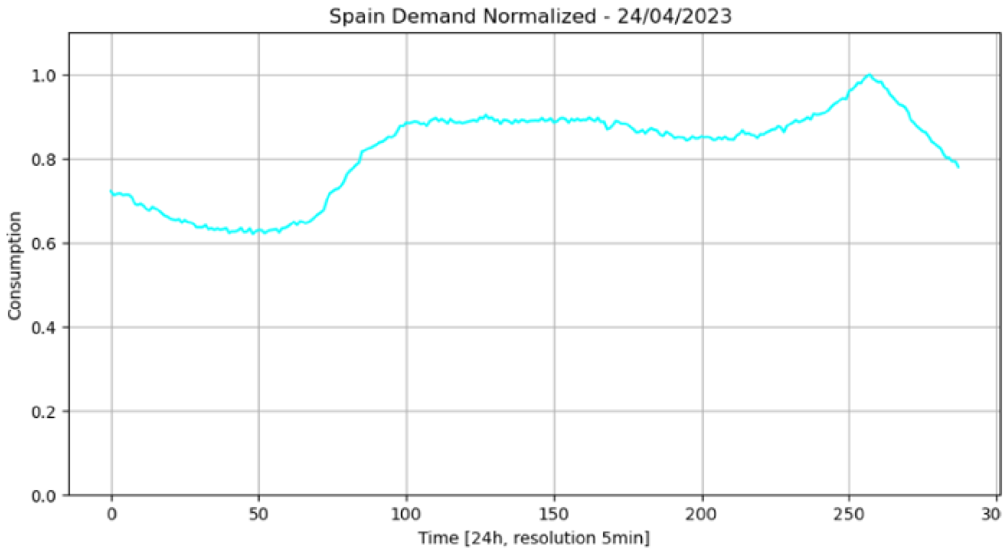

Figure 4: Normalized demand – 24/04/2023

The Demand Normalized graph provides a clear visualization of the normalized energy demand in Spain over a 24-hour period. The demand is measured every 5 minutes, which provides a high-resolution depiction of energy consumption throughout the day. The values are normalized, which is often done to bring all values within the same range between 0 and 1 and allow for an easier comparison between different data. We exported the data from Red Eléctrica de España [14] and subsequently imported it into an Excel spreadsheet, which we used to draw the chart plot.

• **Renewable Generation Data:** In a similar manner, the wind and solar generation data was sourced, normalized and visualized.

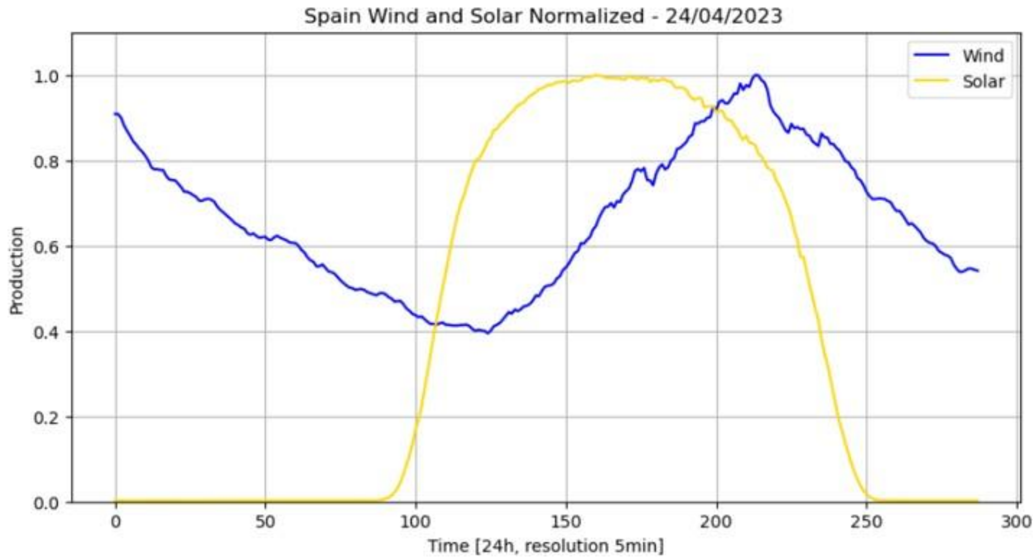

Figure 5: Normalized wind and solar generation – 24/04/2023

The Wind and Solar Normalized chart display the normalized production of wind and solar power in Spain over the same 24-hour period, again at a high resolution of every 5 minutes.

In this graph, two curves are displayed, one for wind power and the other for solar. As can be observed from the chart, the dynamically changing properties of both technologies are displayed. For instance, solar power production would be expected to peak during daylight hours and fall to zero during the night. Wind power production, on the other hand, could vary more unpredictably depending on weather conditions.

Comparing these two graphs can show how well supply from these renewable energy sources meets demand at different times of the day. For example, periods where supply exceeds demand provide us with an opportunity for energy storage, while periods where demand exceeds supply indicate when additional energy sources – like non-renewable thermal generation sources – are needed.

After compiling and organizing the above data, we utilized the Gurobi Optimization platform [23] to define and solve our economic dispatch problem. The objective of our model is to minimize the total cost of power generation over the given time horizon. The cost includes the generation cost for each type of generator and the cost associated with any unmet demand, represented by ENS cost. The Gurobi optimizer provides the optimal dispatch schedule for each generator. The result is a cost-efficient dispatch schedule which fulfills the demand using the available generation capacity.

3.2 Annual economic dispatch model

3.2.1 Introduction

In the field of energy economics and policy-making, the annual economic dispatch model is important for decision-making in terms of long-term planning. The model offers a holistic view of the operation of different energy sources over the entire year.

The model uses daily average data points to capture a broad overview of the energy landscape, which points out the seasonal variations of different energy sources. For instance, the productivity of solar power can be expected to peak during the summer and dip during winter, while the wind generators are expected to have less predictable patterns. Other operational exceptions that cannot be seen on the daily time scale can also be observed here, such as power outages, scheduled maintenances and technology upgrades.

However, while the annual model provides us with a broader view, it lacks the details needed for specific purposes like investment modeling. Investment decisions tend to require more granular data, so that they can calculate the expected return on investment more accurately.

3.2.2 Annual demand

The demand fluctuates not only over the course of a day but also varies seasonally. That is due to weather conditions and societal norms. Much in the same way as for the daily model, we extracted our demand data from Red Eléctrica de España [13]. For the purposes of this study, we concentrate on the demand for an entire year - the year of 2022, which is examined as a representative of annual demand in Spain [24].

3.2.3 Generation technologies

In the annual economic dispatch model, the three generation technologies utilized remain the same as in our daily analysis: wind, solar and thermal power. Each presents unique features, constraints, and capacities, forming a balanced energy generation framework that fulfills the yearly demand.

The solar annual profile manifests a predictable pattern, with peak production occurring during summer months due to increased solar irradiation and dips during winter due to reduced daylight hours. Spain, renowned for its abundant solar irradiation, harnesses this potential significantly, resulting in a heavy reliance on this renewable energy source within our model.

The wind power generation profile in Spain offers different dynamics throughout the year. The country's geography, with its mountain ranges and coastlines, results in areas with high wind potential. Certain global weather patterns, such as the Atlantic wind systems affecting northwestern regions such as Galicia, lead to higher wind generation in specific seasons. A close analysis of annual wind production data reveals a somewhat less predictable pattern compared to solar, as wind speeds and directions can fluctuate due to various meteorological factors.

The thermal power generators act as a buffer, stepping in during periods when renewable sources cannot satisfy the demand. While these conventional generators provide stability and consistency, their high operational costs and environmental footprint make them a last resort in our model.

3.2.4 Objective function

In the Annual Economic Dispatch Model, the objective function remains the same as in the daily model. It represents the total cost of energy generation from each type of generator and the cost of any energy not supplied (ENS), across all time periods within a year.

$$\sum_{t}\left(\sum_{g}\left(C_{W} \times v_{w_{(g,t)}} + C_{PV} \times v_{pv_{(g,t)}} + \left(C_{THa} + C_{THb} \times v_{th_{(g,t)}} + C_{THc} \times \left(v_{th_{(g,t)}}\right)^{2}\right)\right) + C_{ENS} \times v_{ens_{(t)}}\right)$$

Equation 6: Annual economic dispatch objective function

A key difference in the annual model is the scale and timeframe. This optimization is done over an entire year, which accounts for long-term variability in demand and generation, and can suggest the potential for storage. The main goal, as before, is cost minimization while ensuring the demand is met reliably throughout the year.

3.2.5 Power balance constraint

The power balance constraint remains a critical aspect in the annual economic dispatch model. The power balance constraint ensures that the total power produced by all generators, along with the energy not supplied, equals the total demand at all times. This is represented by the following equation:

$$\sum_{g}\left(Vpv_{(g,t)} + Vw_{(g,t)} + Vth_{(g,t)} \right) + Vens_{(t)} = QD_{h.norm(t)} \times QD$$

Equation 7: Annual economic dispatch power balance constraint

Although the structure of this constraint remains unchanged, the scale extends over an entire year in the annual model. The constraint now operates on the yearly energy demand and generation profiles. It helps maintain the balance between supply and demand, ensuring that the system functions reliably throughout the year.

3.2.6 Generator constraints

Just like in the daily model, the generator constraints in the annual economic dispatch model ensure that the power produced from each generator does not exceed its maximum generation capacity. These constraints relate to wind power, solar power, and thermal power generation:

$$Vw_{(g,t)} \leq QW_{h.norm(g,t)} \times QW$$

Equation 8: Wind generator constraint

$$Vpv_{(g,t)} \leq QPV_{h.norm(g,t)} \times QPV$$

Equation 9: Solar generator constraint

$$Vth_{(g,t)} \leq QTH_{h.norm(g,t)} \times QTH$$

Equation 10: Thermal generator constraint

These constraints ensure that the model remains physically feasible by not overestimating the potential of the power production. They respect the specific characteristics and limitations of each generation source, ensuring that the solutions offered by the model do not exceed the physical capabilities of the different generation technologies.

3.2.7 Input parameters

Most of the input parameters for the annual economic dispatch model remain the same. That includes information related to power generators, load demand, and costs. To briefly summarize, the model involves three types of power generators (wind, solar PV, and thermal), demand, and a cost for energy not supplied.

There are, however, certain adaptations in the model to accommodate the shift from a daily to an annual timeframe:

• **Time horizon and periods:** unlike the daily model that operated over a 24-hour period divided into 288 periods (each representing a 5-minute interval), the annual model operates over a full year. In this case, each period corresponds to one day, resulting in 365 periods for the year.

• **Generation capacities:** while the total technology capacities for wind and solar remain the same, amounting to 30 GW each, the capacity for the thermal generation technology has been modified. In the previous model, we used thermal generation technology with a capacity of 5 GW. However, for the annual model, the capacity is adjusted to match the findings from the daily model, which indicated the need for increased capacities. That is why we increased the thermal capacity to match wind and solar capacities at 30 GW. This change aims to create a system capable of covering all of the demand.

• **Demand Data:** The annual model broadens the timeframe to consider the energy demand data for the entire year. This demand data is normalized and visualized in a similar manner to the daily model.

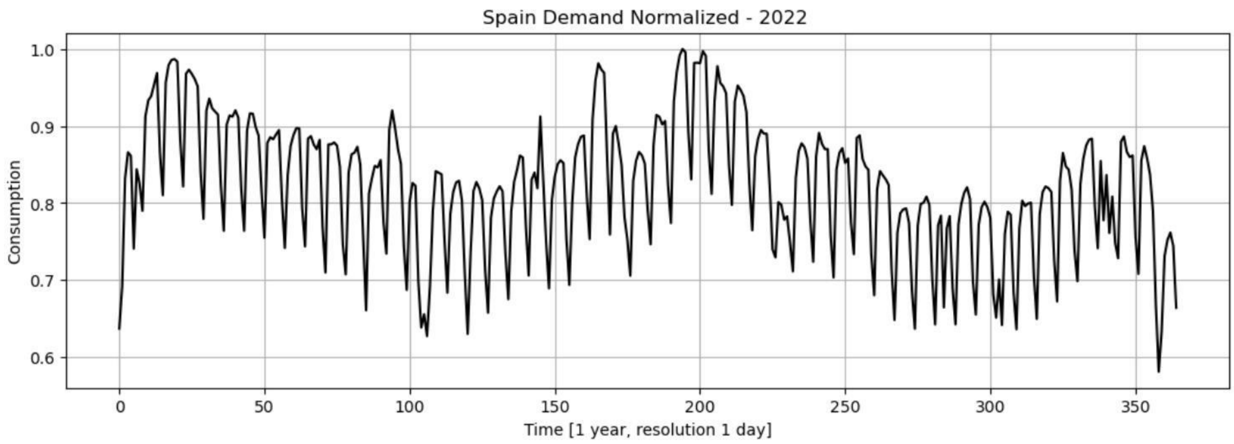

Figure 6: Normalized annual demand - 2022

The graph illustrates the normalized annual energy demand in Spain for 2022, with the demand data measured daily. Seasonal peaks and troughs can be observed due to weather variations and societal routines.

• **Renewable Generation Data:** Similarly, the wind and solar PV generation data were sourced, normalized, and visualized over the course of a year. These data points are instrumental in determining the optimal power dispatch from these generators.

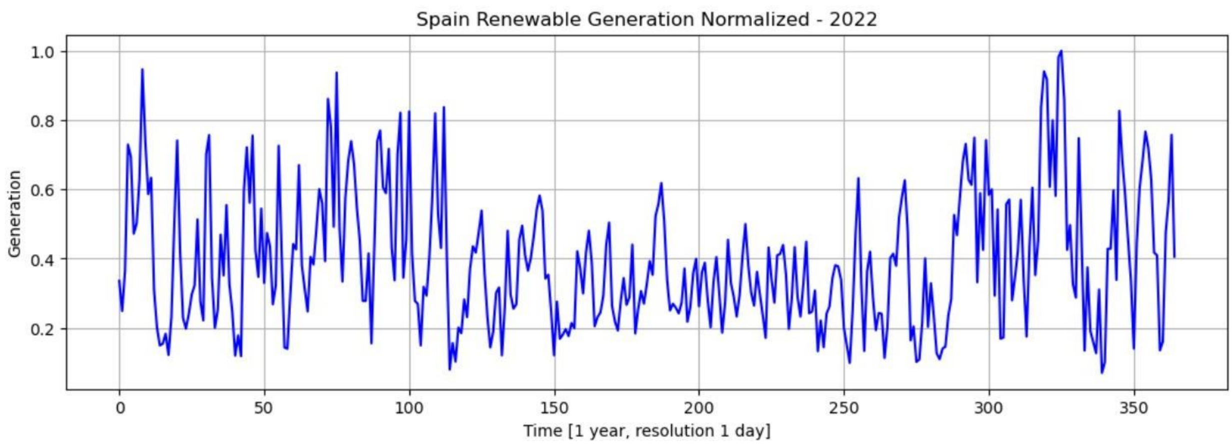

Figure 7: Normalized wind annual generation - 2022

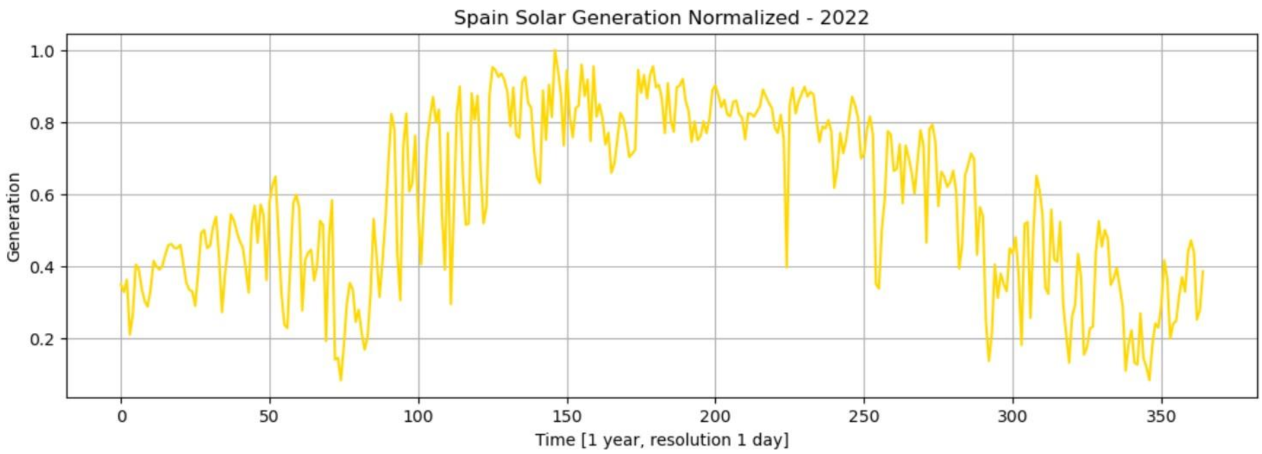

Figure 8: Normalized solar annual generation - 2022

The wind and solar normalized charts represent the normalized production of wind and solar power in Spain over the year 2022. Analogous to the demand graph, the production values are normalized.

Solar power production, as expected, peaks during summer months and diminishes during winter months. Wind power production, however, fluctuates less predictably, even though a more stable wind activity can be observed in the summer months. These present valuable data that can inform strategies for optimizing the integration of renewable energy sources, planning for energy storage solutions, and anticipating the need for additional energy sources.

We continue to use the Gurobi Optimization platform to solve our annual economic dispatch problem [23]. The ultimate objective remains the same: to minimize the total cost of power generation over the given time horizon while ensuring the feasibility of the system.

3.3 Investment model

3.3.1 Introduction

The investment model is essentially a long-term planning tool. It's designed to devise strategies to meet the projected power demands in the future by investing in new generator capacities. While the economic dispatch model is centered around optimal dispatch of existing power units, the investment model deals with strategic development of the infrastructure of the energy generation system.

When analyzing the costs of the investment model, we must include both investment costs and future operational costs. Renewable power sources historically had higher installation expenses with lower operating costs, offering us a potential for future savings. Therefore, the investment model has always played a pivotal role when considering renewable energy infrastructure. Recently, the cost of photovoltaic panels has decreased significantly, rendering them an exceptional investment choice among all power sources.

While both the economic dispatch and the investment model play essential roles in power system operation, they use a distinct approach in dealing with different time horizons and decisions. The first carries out the optimal operation of existing power resources, while the latter is a strategic, long-term planning tool with a focus on the sustainable development and expansion of power systems.

3.3.2 Demand

In the investment model, the demand is addressed in a different from that in the economic dispatch model. It remains the driving force that determines the quantity of energy that ought to be generated, but this model is designed to address both present and future demands. The model plans for the evolution of daily demand shifts in energy consumption patterns, instead of only catering to current power needs.

In the context of our study, we're using the same daily demand data from Red Eléctrica de España [14] that we had previously used for the economic dispatch model. Instead of focusing only on the daily demand, we expand the view to anticipate future changes in daily energy consumption. By taking this approach, we design the system to be fit to meet future daily demands.

3.3.3 Generation technologies

In our study, we continue to use the same three types of energy generation technologies as we did in our previous analysis: solar power, wind power, and thermal power. Generation technologies primarily consist of renewable sources, taking advantage of the country’s favorable weather conditions. Thermal power serves as a reserve for instances when the previously mentioned technologies fall short of attaining the demand. We once again use the same data from

Red Eléctrica de España [14] for our solar and wind energy production profiles, as well as demand.

3.3.4 Objective function

The objective function continues to represent the cost minimization goal but now introduces a new element: investment costs. Alongside the costs of producing the required quantities of energy, we now also account for the cost of investing in generation technologies.

$$\sum_{t}\left(\sum_{g}\left(C_{W} \times vw_{(g,t)} + C_{PV} \times vpv_{(g,t)} + \left(C_{THa} + C_{THb} \times vth_{(g,t)} + C_{THc} \times \left(vth_{(g,t)}\right)^{2}\right)\right) + C_{ENS} \times vens_{(t)}\right) + C_{invw} \times iw + C_{invpv} \times ipv + C_{invth} \times ith$$

Equation 11: Investment model objective function

Costs of energy generation from wind, solar, thermal and ENS are represented by *(CW × vW(g, t)), (CPV × vPV(g, t)), (CTa + CTb × vt(g, t) + CTc ×* $(vt(g, t))^2$*),* and *(CENS × vENS(t))* respectively. Those are summed across all generators and time periods. As in the economic dispatch model, *CW, CPV*, and *(CTa, CTb, CTc)* are the cost coefficients for each respective technology, while *vW(g, t), vPV(g, t)*, and *vt(g, t)* are the volumes of energy generated by each technology during the 24-hour period.

In the investment model, new elements are presented. These are*: CinvW × iw, CinvPV × ipv*, and *CinvTH × ith*. These represent the investment costs for wind, solar, and thermal power generation technologies, respectively. These terms are added to the objective function to account for the upfront costs of investing in each type of generator. The *CinvW, CinvPV*, and *CinvTH* variables represent the cost of investment in each technology type, and *iw, ipv*, and *ith* are the investment variables that represent the invested capacities in each generation technology.

3.3.5 Power balance constraint

The power balance constraint remains a key component in our investment model, just like it did in the economic dispatch model. The constraint is given by the equation:

$$\sum_{g}\left(vpv_{(g,t)} + vw_{(g,t)} + vth_{(g,t)}\right) + vens_{(t)} = QD_{h.norm(t)} \times QD$$

Equation 12: Investment model power balance constraint

The equation ensures that at every time period, the total power generated equals the total demand.

In the investment model, the power balance constraint has an expanded role. The constraint prevents over- or under-investment in energy capacity and thus guides the investment decisions towards practical solutions. It conveys that any investment in new capacities must also align with the balance of supply and demand, ensuring investment efficiency and system reliability.

3.3.6 Generator constraints

Generator constraints ensure that any proposed energy production is physically feasible. In the economic dispatch model, these constraints were tied to the existing capacity of each power source. However, the investment model considers strategic decisions related to increasing generation capacity. Constraints in the investment model are therefore adjusted to reflect potential changes in generation capacity.

Here are the adjusted generator constraints in the investment model:

$$vw_{(g,t)} \leq QW_{h.norm(g,t)} \times i_w$$

Equation 13: Wind generator constraint

This constraint dictates that at any given moment, the power output from the wind generator, *vW(g, t),* does not exceed the available wind power capacity. The term *QWh.norm(g,t)* symbolizes the normalized wind generation profile, and iw is the new investment variable, which reflects the additional generation capacity of wind power that's considered for investment.

$$vpv_{(g,t)} \leq QPV_{h.norm(g,t)} \times i_{pv}$$

Equation 14: Solar generator constraint

This constraint, structured in the same way as the previous one, applies to solar power. It states that the power generated from each photovoltaic unit, *vPV(g, t),* should not surpass the maximum power output possible with the number of PV units invested in ipv. *QPVh.norm(g,t)* represents the normalized solar power profile.

$$vth_{(g,t)} \leq Q_{THh.norm(g,t)} \times ith$$

Equation 15: Thermal generator constraint

The final constraint applies to thermal power, insisting that the power output from the thermal generator, *vTH(g, t),* should not exceed its maximum generation capacity. This maximum capacity is determined by the additional thermal power capacity under consideration for investment, represented by ith. *QTHh.norm(g,t)* symbolizes the limits of the installed thermal capacity.

3.3.7 Input parameters

In the investment model, we continue using the same input parameters as in the economic dispatch model. By maintaining these inputs the same in both models, we make sure the models are consistent and that we can compare the results more easily.

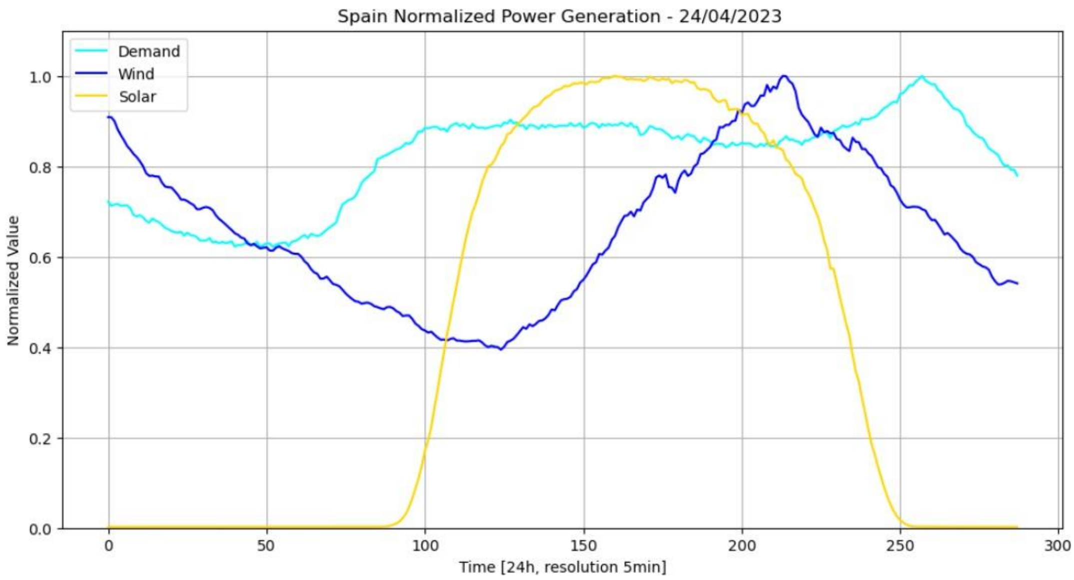

Figure 9: Normalized demand, wind and solar production – 24/04/2023

This combined graph gives us a simple but clear picture of energy in Spain for a full day, as part of our investment model study. We can see how energy use, wind power, and solar power change at every 5-minute interval.

After gathering the required data, we proceeded to solve the investment problem using the Gurobi optimization platform [23]. The objective is to minimize the total cost of power generation. That includes the generation costs for each type of generator as well as the costs of adding new capacity.

Chapter 4: Results

4.1 Economic dispatch model

4.1.1 Dispatched values

The process of energy dispatch in power systems presents a crucial step towards accomplishing the project's goals. It involves continuous adjustments to meet energy demand efficiently while considering the changing nature of renewable energy sources. To visualize these operations, four charts are presented - each showcasing the dispatch for a different energy source: wind, solar, thermal, and energy not supplied.

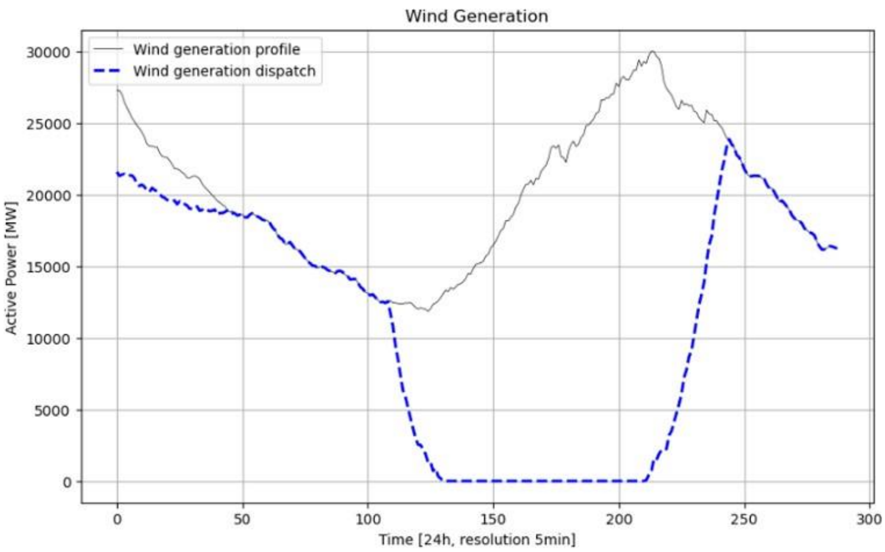

Figure 10: Wind dispatched generation

The wind energy dispatch chart provides a picture of the available generation and the actual dispatch of wind power throughout the day. This perspective serves as a useful comparison, highlighting the inherent variability of wind power.

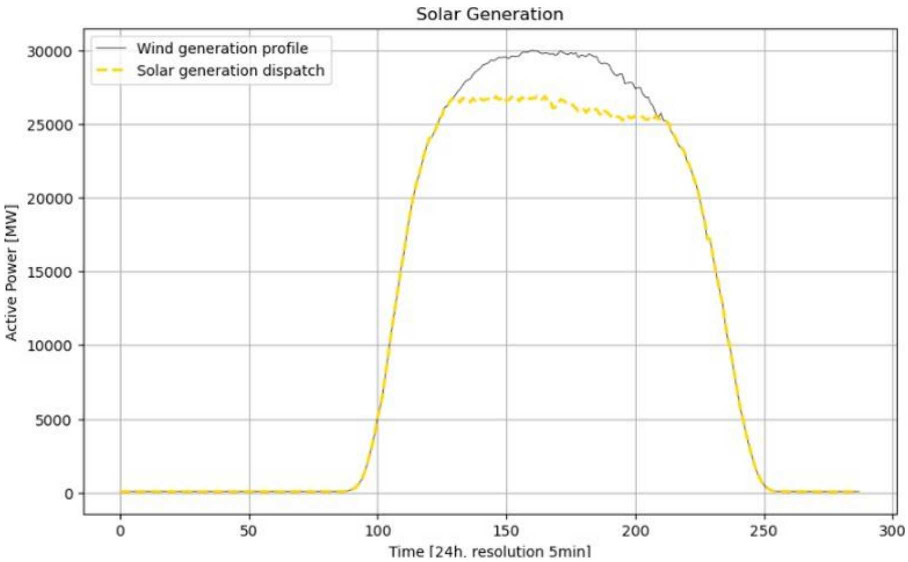

Figure 11: Solar dispatched generation

The solar energy dispatch chart shows both planned and actual solar power generation in the same way. It illustrates the influence of environmental factors like sunlight variability on solar energy dispatch. It can be easily observed during which time of the day the solar production is at its highest, and when there's no generation due to the lack of the sun's presence. As mentioned earlier, solar energy on the market is cheaper than wind, which explains the system's optimization preference to dispatch solar energy over wind. Having this graph in mind, the sudden dip in the curve of wind dispatched energy makes perfect sense, as solar generation covers all of the demand in most of the time periods when the solar generator is active.

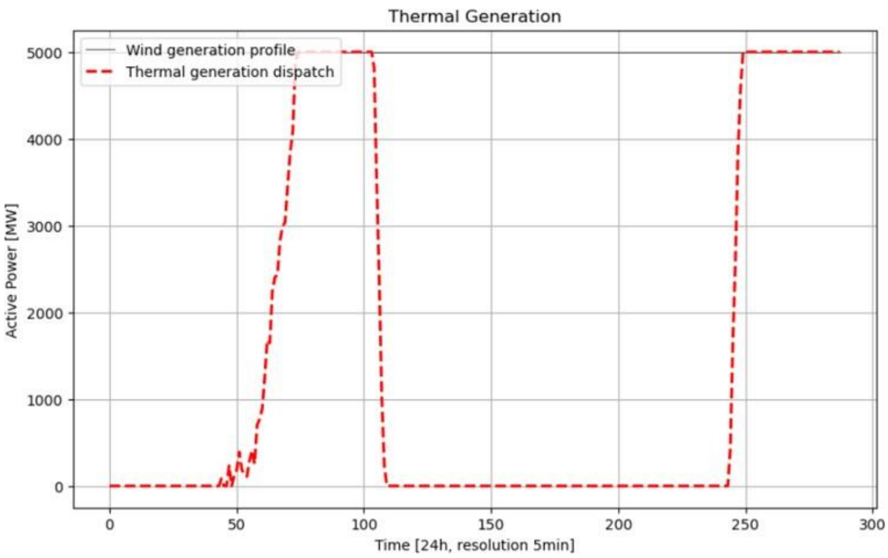

Figure 12: Thermal dispatched generation

The thermal energy dispatch chart presents the use of thermal energy in our power system. The upper limit of thermal power generation, set at 5000 MW, illustrates the physical constraints associated with this form of power. In contrast to renewable sources, thermal energy is dispatched only when the collective output from wind and solar generation fails to meet the total demand. This selective usage is primarily due to the high operational costs associated with thermal power generation.

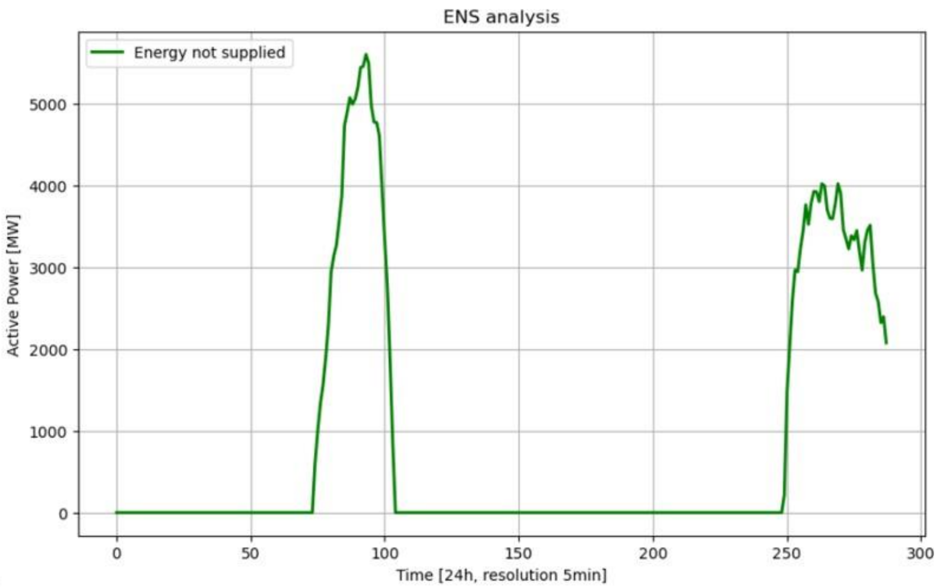

Figure 13: ENS dispatched

The energy not supplied chart displays those instances when the total demand was not met by the cumulative energy generation from all sources. These instances, although undesirable, are key indicators of demand-supply imbalances in the system. From the graph, we observe that this occurs during peak demand periods, which poses a challenge for a system that relies predominantly on variable renewable energy sources.

All these charts, taken together, illustrate the dynamic nature of energy dispatch and the constant adjustments needed to balance supply and demand, particularly in systems that rely heavily on variable renewable energy sources.

4.1.2 Generation curtailments

The curtailment charts illustrate the so-called curtailed or undispatched energy from wind and solar power sources. This curtailed energy refers to the generation potential that was not utilized or dispatched into the grid.

The charts display the difference between the potential wind and solar energy that could have been generated as per the initial plan and the actual dispatched wind and solar energy respectively.

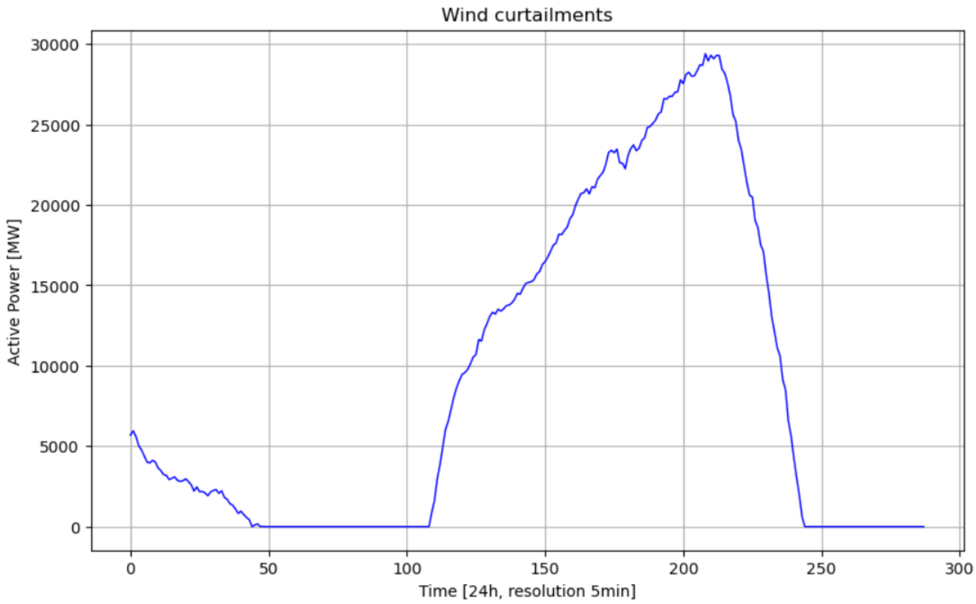

Figure 14: Wind curtailments

The analysis of the wind curtailments reveals two distinct periods of curtailment. The first, although relatively less significant than the second, occurs during the early hours of the day when the dispatched wind energy alone is sufficient to meet the demand. The second period of curtailment arises when lower-priced solar energy is prioritized over wind production, effectively fulfilling the demand without relying on wind power.

Wind Curtailments [MWh]	Wind Dispatched Generation [MWh]
214.943,90	262.607,67

Table 1: Wind curtailments and dispatched generation

In addition, the table provides the numerical values of the total amount in MWh of wind curtailments and compares them to the total dispatched generation of the wind generation technology. We can observe that the curtailments reach almost the same value as the dispatched generation, meaning that a significant portion of the available generation does not get dispatched.

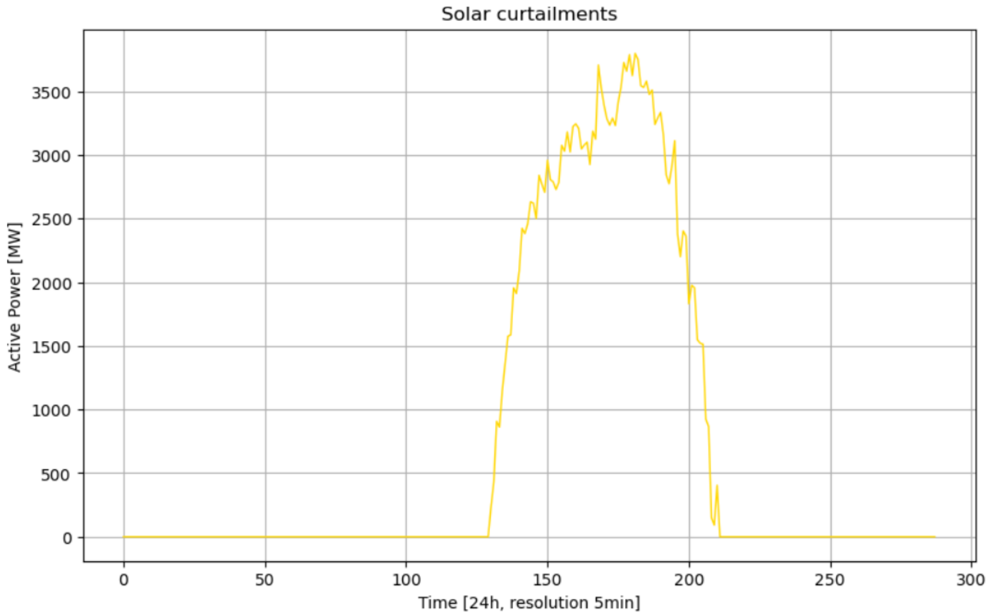

Figure 15: Solar curtailments

Observing the solar curtailments chart, we can easily conclude that curtailments occur exclusively during daylight hours when the solar generator is actively producing power. That is because curtailments result from an excess of generated energy surpassing the actual demand. Consequently, the surplus energy is curtailed to maintain a balance between power supply and demand, in accordance with the power balance constraint.

Solar Curtailments [MWh]	Solar Dispatched Generation [MWh]
17.439,15	272.902,97

Table 2: Solar curtailments and dispatched generation

A table depicting those same values is also provided. The table depicts the proportions between the solar curtailments and solar dispatched generation. Understandably, the dispatched generation is significantly greater than the curtailments, knowing that the solar generation dispatch gets prioritized over any other, due to the already well-known cost advantages.

Understanding and visualizing curtailment is important for resource optimization. If curtailments are relatively low, investing in storage technologies might not be economically profitable. High levels of curtailments on the other hand, tell us that there are opportunities for optimization and storage technology could be considered. This way, the otherwise wasted potential could be recaptured.

4.1.3 Total curtailments with demand and ENS

This comprehensive chart presents a holistic perspective of energy management. It simultaneously represents total energy demand, Energy Not Supplied (ENS), and curtailments, demonstrating the important relationships and dynamics within the system. Total demand represents the complete quantity of energy required over a specific time period, serving as a fundamental reference point, as meeting this demand is the primary goal of any energy system. The ENS curve signifies instances where the demand could not be adequately met by the system, while curtailments represent the total amount of generated energy that was not utilized by wind and solar generators.

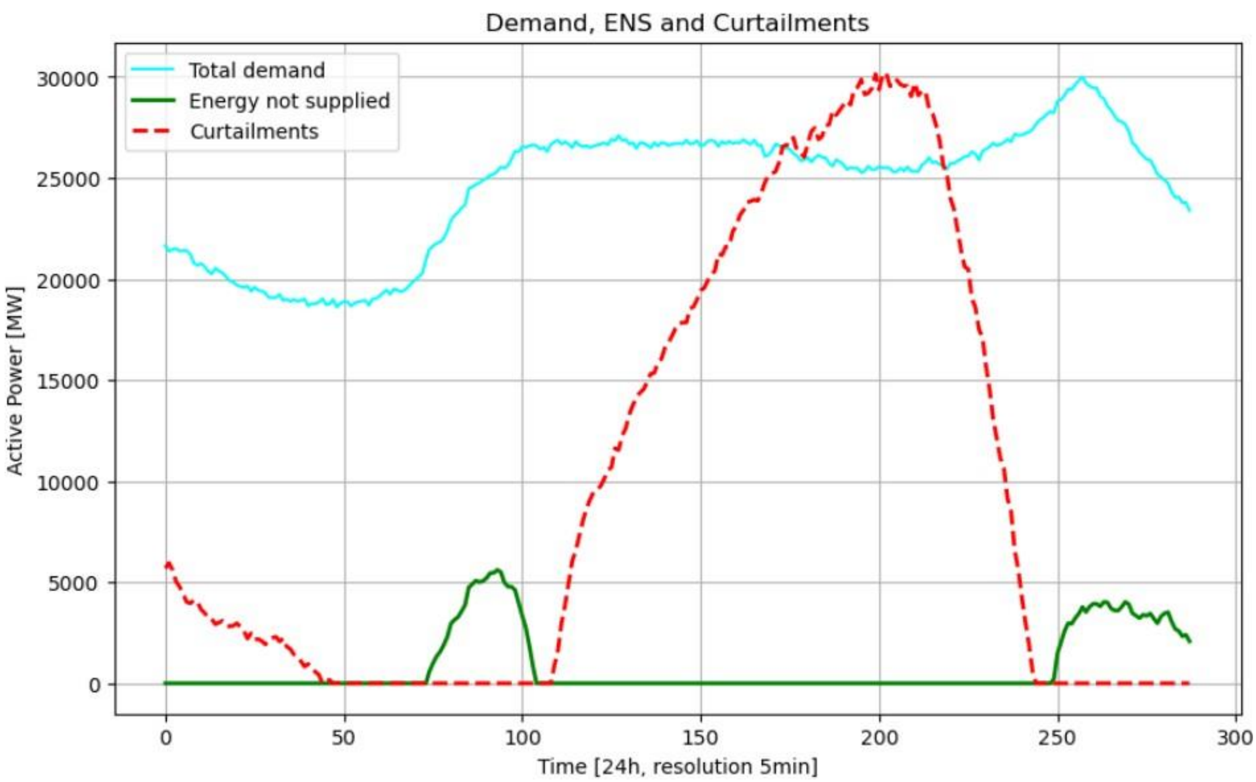

Figure 16: Demand, ENS and curtailments

As can be seen from the chart, at some instances the curtailment values even surpass the demand, indicating that the system might have an overabundance of generation capacities at certain times. By combining these three elements in a single graph, we obtain a more nuanced understanding of the energy system's efficiency, reliability, and capacity for harnessing renewable energy sources. It highlights the periods of over-generation and can give us indications on how to better optimize the system.

4.1.4 All energy sources with total demand

The chart offers a comprehensive visual representation of how different energy sources contribute to meeting the total energy demand over time. We can observe the contributions of wind, solar, and thermal energy sources as individual lines, each representing the amount of active power dispatched from these sources at each point in time. This allows us to observe the temporal variability in output for these different resources. Wind and solar power, being intermittent sources, display variability based on weather conditions, while thermal generation can be controlled more directly and is used in response to peaks in demand, when the renewable sources are unable to fulfill the demand in the given instance. The Energy Not Supplied (ENS) line shows instances where the energy demand exceeds the total generation capacity. Lastly, the chart displays the total demand values at every interval.

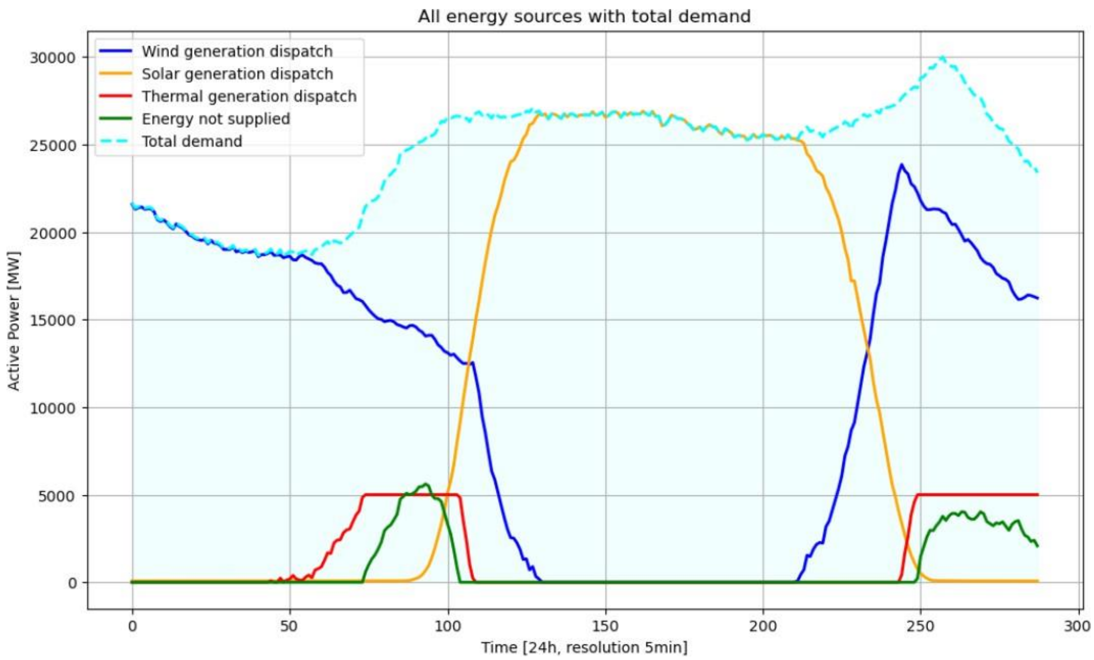

Figure 17: All energy sources with total demand

As noted earlier, consistent or high ENS could indicate issues in the system, suggesting a need for increased generation capacity, grid upgrades, or improved management strategies. The area under the total demand curve represents total energy production in the day. We can observe that solar and wind are the predominant sources of power generation, given their cost advantage compared to thermal production. During peak daylight hours, solar power fulfills most of the demand. We can also observe peak demand periods, occurring twice daily, once in the morning and once in the evening, during which thermal energy production increases significantly. However, even thermal power becomes insufficient to cover the total demand, thereby forcing the utilization of ENS to supplement the remaining demand. This combined visualization can facilitate understanding of how different sources work together to meet fluctuating demand,how reliable the current system is, and how it can be adjusted to achieve a better balance between demand and supply. It highlights the periods of under-generation and can give us indications on how to better optimize the system.

4.1.5 Hourly dispatch production

The presented bar chart displays the energy generation from different sources on an hourly basis. This format offers a different perspective from the previous line graph, facilitating the observation of average contributions from each energy source within an hour.

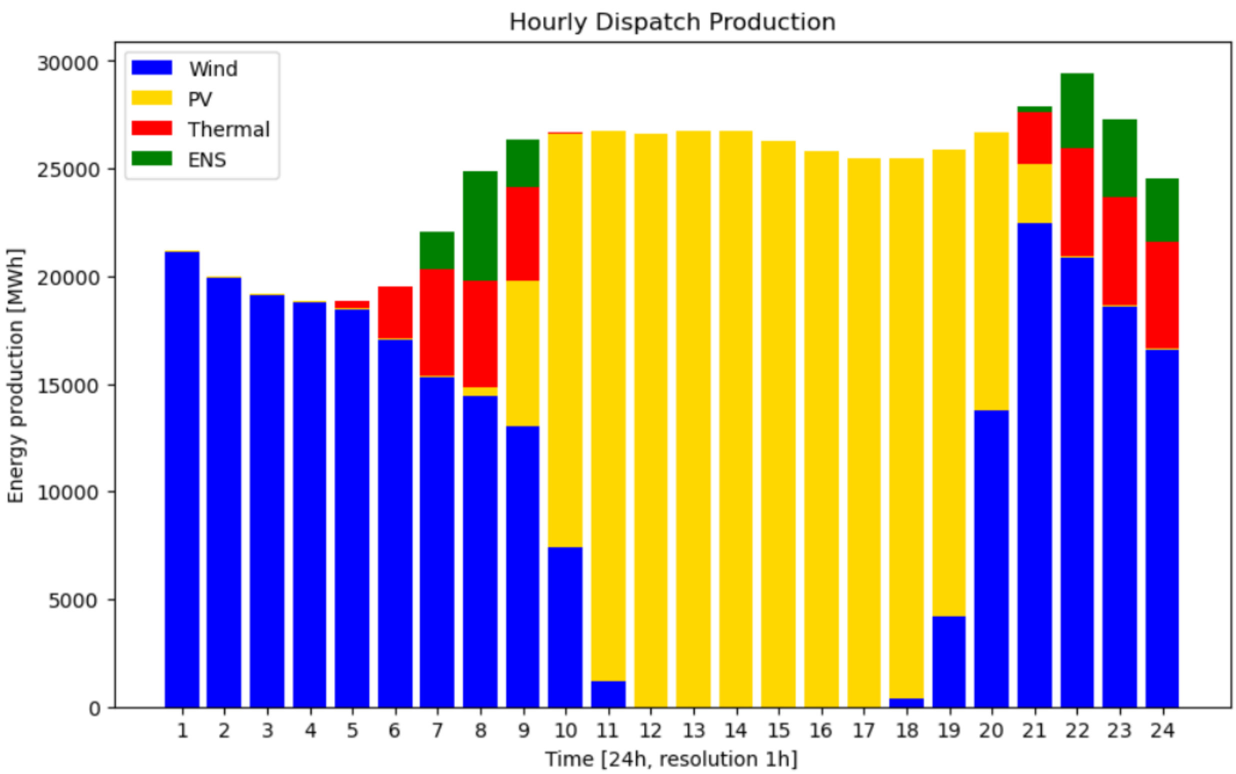

Figure 18: Average hourly dispatched production

The bars are stacked upon each other to show the total energy production at each hour of the day, allowing for a direct comparison of the relative contributions of each source. The sum of all bars shows the demand of the system.

In this hourly average representation, the effects of solar and wind variability are smoothed out, providing a clear picture of the overall trends in energy production. It helps in identifying the typical production profile for each source, highlighting hours when each source is most productive.

This hourly breakdown can be particularly useful in assessing the system's performance and reliability over a typical day, and it can aid in making informed decisions about optimizing dispatch strategies and managing energy resources more effectively. The bar graph format also simplifies the depiction of data, making it easier to visualize the contribution of each source to total generation.

	Wind Production	Solar Production	Thermal Production	ENS	Total Production
1	21.111,23 MWh	71,26 MWh	0,00 MWh	0,00 MWh	21.182,49 MWh
2	19.952,33 MWh	71,60 MWh	0,00 MWh	0,00 MWh	20.023,93 MWh
3	19.130,40 MWh	71,43 MWh	0,00 MWh	0,00 MWh	19.201,83 MWh
4	18.772,10 MWh	71,43 MWh	26,32 MWh	0,00 MWh	18.869,85 MWh
5	18.472,41 MWh	70,43 MWh	295,48 MWh	0,00 MWh	18.838,32 MWh
6	17.067,78 MWh	70,43 MWh	2.390,15 MWh	0,00 MWh	19.528,36 MWh
7	15.315,17 MWh	70,43 MWh	4.909,43 MWh	1.798,72 MWh	22.093,75 MWh
8	14.440,56 MWh	375,33 MWh	5.000,00 MWh	5.072,62 MWh	24.888,51 MWh
9	13.001,42 MWh	6.795,73 MWh	4.311,45 MWh	2.245,40 MWh	26.354,00 MWh
10	7.405,80 MWh	19.238,82 MWh	19,43 MWh	0,00 MWh	26.664,05 MWh
11	1.162,32 MWh	25.606,66 MWh	0,00 MWh	0,00 MWh	26.768,98 MWh
12	0,00 MWh	26.646,12 MWh	0,00 MWh	0,00 MWh	26.646,12 MWh
13	0,00 MWh	26.726,80 MWh	0,00 MWh	0,00 MWh	26.726,80 MWh
14	0,00 MWh	26.741,76 MWh	0,00 MWh	0,00 MWh	26.741,76 MWh
15	0,00 MWh	26.265,89 MWh	0,00 MWh	0,00 MWh	26.265,89 MWh
16	0,00 MWh	25.832,11 MWh	0,00 MWh	0,00 MWh	25.832,11 MWh
17	0,00 MWh	25.460,11 MWh	0,00 MWh	0,00 MWh	25.460,11 MWh
18	353,62 MWh	25.155,39 MWh	0,00 MWh	0,00 MWh	25.509,01 MWh
19	4.203,97 MWh	21.656,71 MWh	0,00 MWh	0,00 MWh	25.860,68 MWh
20	13.782,00 MWh	12.873,33 MWh	0,00 MWh	0,00 MWh	26.655,33 MWh
21	22.453,37 MWh	2.790,55 MWh	2.345,21 MWh	311,11 MWh	27.900,25 MWh
22	20.851,20 MWh	99,13 MWh	5.000,00 MWh	3.497,28 MWh	29.447,61 MWh
23	18.570,02 MWh	71,43 MWh	5.000,00 MWh	3.615,49 MWh	27.256,94 MWh
24	16.561,95 MWh	70,09 MWh	5.000,00 MWh	2.918,01 MWh	24.550,05 MWh

Table 3: Hourly dispatched production

The table chart being displayed is a tabular representation of the hourly energy production for each energy source, including wind, solar, thermal, and ENS. It also presents the total energy production for each hour of the day.

This table serves as a useful complement to the bar chart. We are able to precisely see the exact numerical values, making the interpretation of the data easier. The table facilitates cross-verification. This ensures the data’s accuracy of the data processing and visualization.

	Wind	PV	Thermal	ENS	TOTAL
Total Energy Dispatched (MWh)	262.607,667	272.902,969	34.297,477	19.458,623	589.266,735

Table 4: Total dispatched production

The table above presents a summary of the total energy dispatched from the different energy sources - Wind, solar, thermal and energy not supplied.

The primary purpose of summarizing energy production of each technology in this manner is to provide an overview of the distribution of energy used during the day. It can be an important tool in various analyses, from financial considerations to operational and strategic planning. The table also shows the sum of all energy dispatched, which provides an overall sense of the scale of the energy system and its demand.

By displaying this data in a tabular format, it allows for a quick understanding of the proportion of different energy sources in the total energy dispatched. This can be used to make informed decisions on potential areas for improvement or investment. It can also be used for monitoring and optimizing the overall performance of the power grid.

4.1.6 Dispatch cost analysis

To fully comprehend the economic efficiency of our energy dispatch system, a thorough understanding of the associated costs is required. Different energy sources come with their distinctive cost structures.

$$w_{cost} = v_w \times C_W \div 12$$

Equation 16: Wind generation cost

$$pv_{cost} = v_{pv} \times C_{PV} \div 12$$

Equation 17: Solar generation cost

$$th_{cost} = (900 + v_{th} \times 45 + v_{th}^2 \times 0.01) \div 12$$

Equation 18: Thermal generation cost

$$total_{cost} = w_{cost} + pv_{cost} + th_{cost}$$

Equation 19: Total generation cost

The above equations demonstrate how the production cost of the economic dispatch model is calculated. The cost of each energy source is calculated by multiplying the power production of the generatorin each interval by the cost per MWh of that commodity. As we have 5-minute intervals, we have to divide the product by 12, to account for the difference in time scale. This step converts the units from 300 Megawatt-seconds (reflecting the 5-minute intervals) into Megawatt-hours. The cost of thermal power generation is calculated in the following way: the base cost of 900 € is added to the price of multiplying energy production in each interval by 45 € / MWh with an additional term representing the square of thermal dispatch multiplied by 0.01 € / MWh^2. This represents non- linear cost elements associated with thermal power generation, such as efficiency losses at higherloads. The total equation is then divided by 12 to obtain the production cost value in every 5- minute interval. The final cost consists of the sum of all the other costs.

The following 'Dispatch cost' graph provides a detailed illustration of the accumulated expenses of energy dispatched from all wind, solar, and thermal generators within each 5-minute interval, showcasing the fluctuating costs associated with each source overtime.

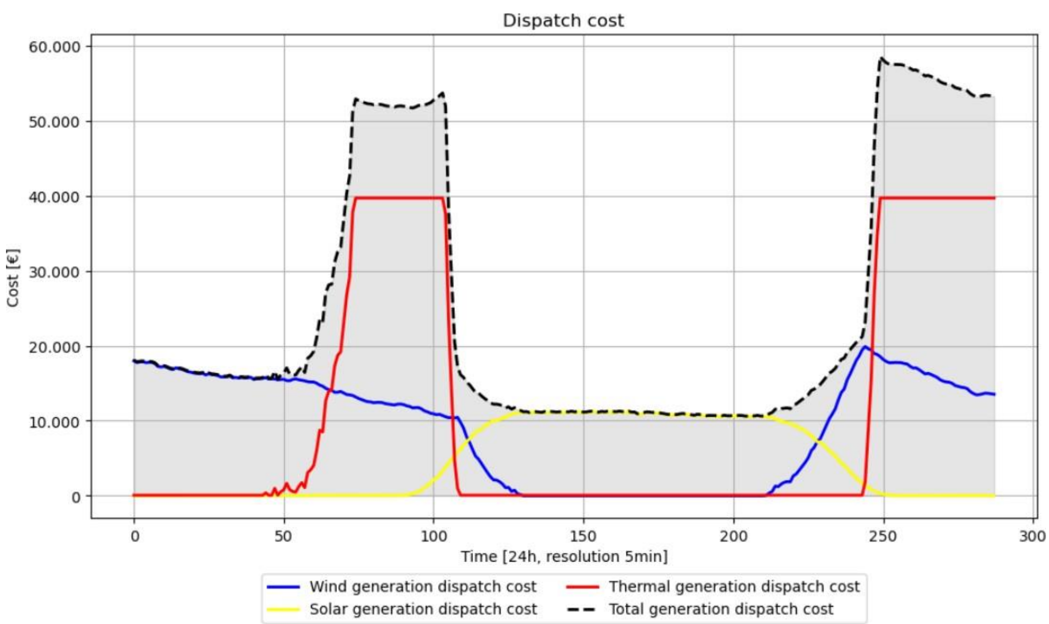

Figure 19: Dispatched production cost

The graph illustrates the accumulated expenses of energy dispatched from all wind, solar, and thermal generators within each 5-minute interval. This plot is particularly useful in providing a clear comparison of the costs associated with dispatching energy from different sources. It shows how these costs change over time. The total cost line provides a quick visual reference for the sum of costs from all sources.

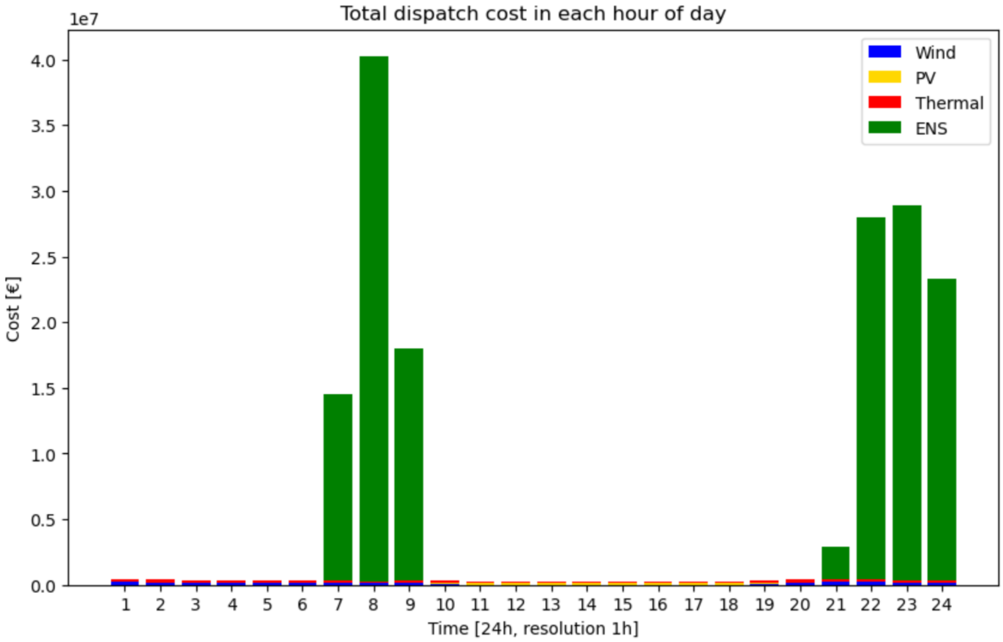

Figure 20: Total dispatched production cost in each hour

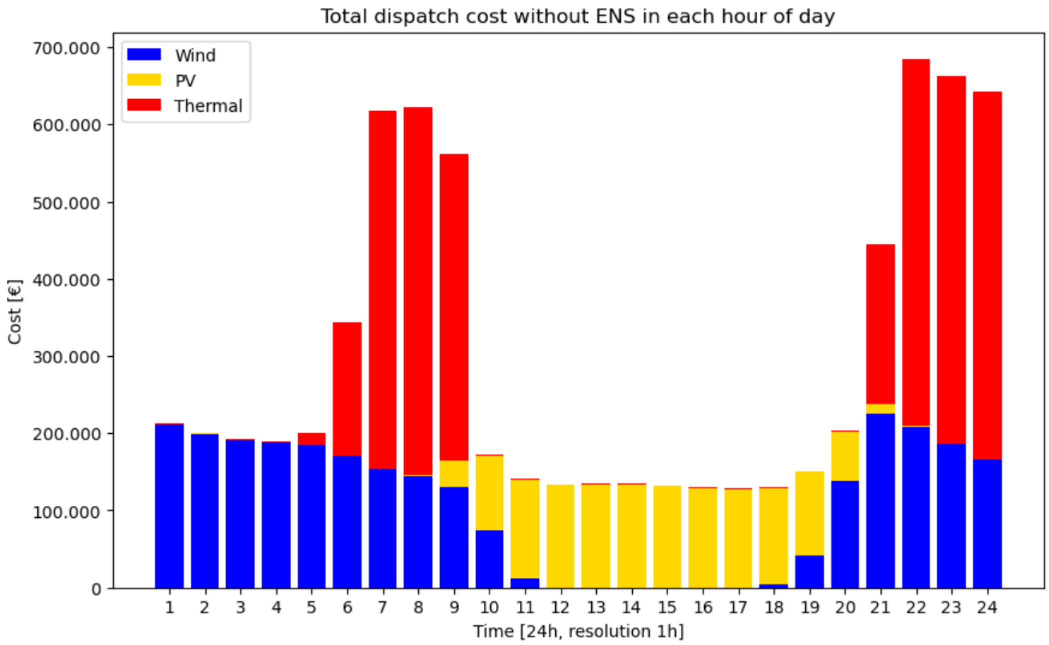

Figure 21: Total dispatched production cost without ENS in each hour

These bar charts depict the total dispatch cost in each hour for each of the power generation technologies. It breaks down the cost data into an hourly format, shows the cost for the energy generated every hour, and presents this information in a stacked bar plot.

	Wind Dispatch Cost	Solar Dispatch Cost	Thermal Dispatch Cost	ENS Dispatch Cost	Total Dispatch Cost
1	211.112,30 €	356,31 €	900,00 €	0,00 €	212.368,61 €
2	199.523,34 €	357,98 €	900,00 €	0,00 €	200.781,32 €
3	191.303,99 €	357,14 €	900,00 €	0,00 €	192.561,14 €
4	187.721,02 €	357,14 €	2.135,17 €	0,00 €	190.213,34 €
5	184.724,06 €	352,14 €	15.584,70 €	0,00 €	200.660,89 €
6	170.677,84 €	352,14 €	172.949,56 €	0,00 €	343.979,54 €
7	153.151,72 €	352,14 €	463.505,73 €	14.173.942,61 €	14.790.952,19 €
8	144.405,62 €	1.876,67 €	475.900,00 €	39.972.230,08 €	40.594.412,37 €
9	130.014,25 €	33.978,64 €	396.821,82 €	17.693.760,57 €	18.254.575,28 €
10	74.058,03 €	96.194,09 €	1.819,71 €	0,00 €	172.071,83 €
11	11.623,17 €	128.033,29 €	900,00 €	0,00 €	140.556,47 €
12	0,00 €	133.230,62 €	900,00 €	0,00 €	134.130,62 €
13	0,00 €	133.633,99 €	900,00 €	0,00 €	134.533,99 €
14	0,00 €	133.708,82 €	900,00 €	0,00 €	134.608,82 €
15	0,00 €	131.329,43 €	900,00 €	0,00 €	132.229,43 €
16	0,00 €	129.160,53 €	900,00 €	0,00 €	130.060,53 €
17	0,00 €	127.300,56 €	900,00 €	0,00 €	128.200,56 €
18	3.536,18 €	125.776,97 €	900,00 €	0,00 €	130.213,15 €
19	42.039,69 €	108.283,54 €	900,00 €	0,00 €	151.223,24 €
20	137.819,98 €	64.366,66 €	900,00 €	0,00 €	203.086,63 €
21	224.533,75 €	13.952,77 €	206.858,46 €	2.451.508,85 €	2.896.853,83 €
22	208.512,01 €	495,66 €	475.900,00 €	27.558.543,17 €	28.243.450,84 €
23	185.700,23 €	357,14 €	475.900,00 €	28.490.039,49 €	29.151.996,87 €
24	165.619,49 €	350,47 €	475.900,00 €	22.993.924,00 €	23.635.793,96 €

Table 5: Total hourly dispatched production cost

Finally, presenting this data in a table along with a bar chart ensures that the information is accessible and comprehensible to a broad audience, catering to both visual and numerical data interpretation preferences.

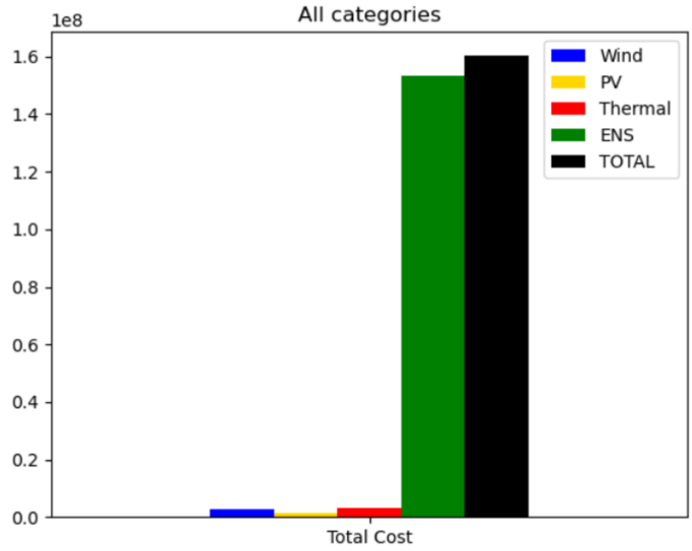

Figure 22: Total cost

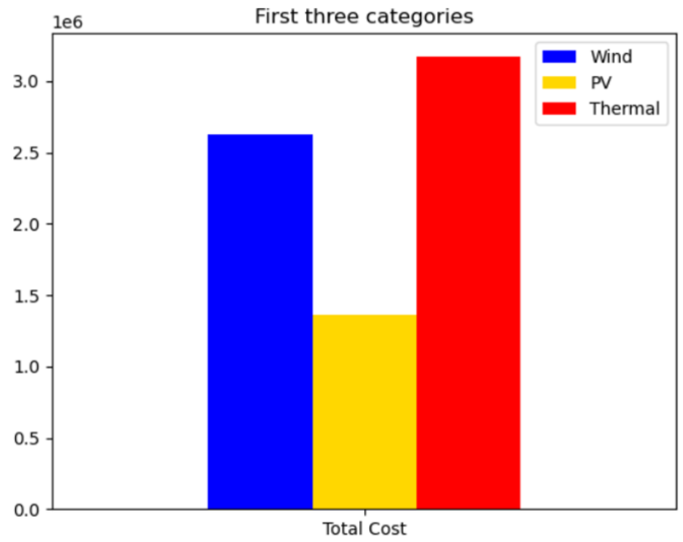

Figure 23: Cost of wind, solar and thermal generators

These depictions visualize the total costs associated with each power generation technology. For easier understanding, we displayed a second bar chart to illustrate the values of wind, solar and thermal generators with greater precision.

	Wind	PV	Thermal	ENS	TOTAL
Total Cost	2.626.076,67 €	1.364.514,84 €	3.174.975,15 €	153.333.948,78 €	160.499.515,44 €

Table 6: Total dispatched production cost

The bar plots are then followed by a table chart that represents the same cost data in a numerical format.

Showing the total cost is useful for a variety of reasons. It provides an overview of the overall expenses associated with the different energy generation methods. This information could guide decision-making processes, such as whether to invest in additional capacity. In our case, we observe a substantial difference between the costs of ENS and all other costs. This points to a potential necessity to increase renewable energy capacities or the implementation of energy storage technologies.

4.1.7 Costs per MWh

Understanding the cost per MWh is a crucial component of energy economics. It offers a clear picture of the cost efficiency of various energy sources - wind, solar, thermal, and Energy Not Supplied (ENS). This metric reflects the overall cost of generating a single unit of electricity, thereby providing a standardized and comparable measure for different energy sources.

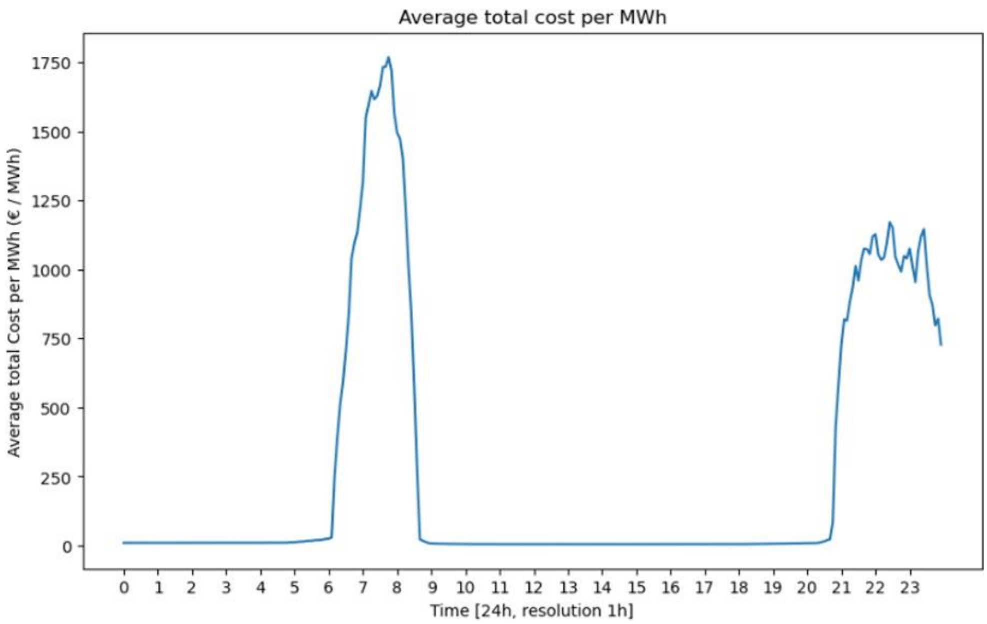

Figure 24: Average total cost per MWh

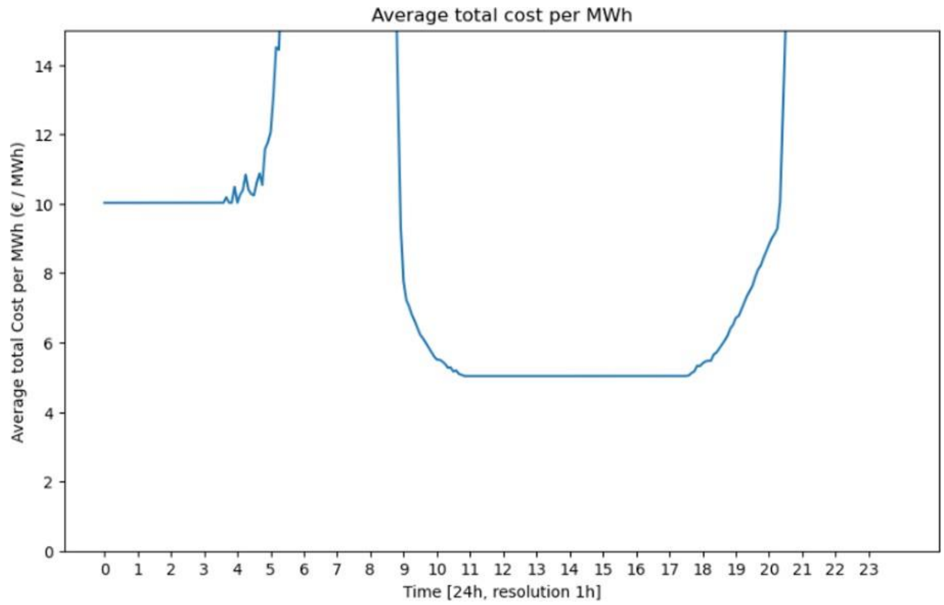

Figure 25: Average total cost per MWh in lower ranges

Firstly, the line plots provide a more detailed perspective of cost dynamics, calculating the cost per MWh in 5-minute intervals. This detailed examination reveals short-term fluctuations in cost efficiency that might not be visible by the broader scope of hourly averages. Two variations of the line charts are provided. The first offers a comprehensive view of the full spectrum, serving as an overview of cost variations across the entire range. In contrast, the second zooms in on the 0-15 €/MWh range, delivering a closer look at the cost variations when the renewable generation is fully covering the demand.

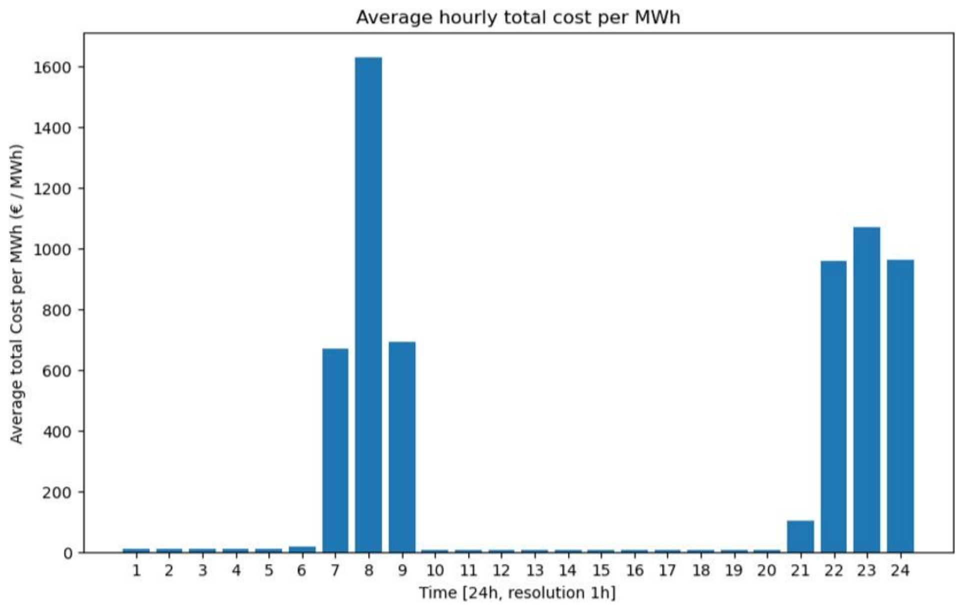

Figure 26: Average hourly total cost per MWh

Complementing the line charts, the bar chart visually demonstrates the total cost per MWh for each hour of the day. It allows for an intuitive grasp of cost fluctuations throughout the day. This visualization enhances the understanding of hourly cost trends and disparities between different energy sources, offering a more engaging representation of the data.

	Wind Cost per MWh	Solar Cost per MWh	Thermal Cost per MWh	ENS Cost per MWh	Total Cost per MWh
1	10,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	10,03 €/MWh
2	10,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	10,03 €/MWh
3	10,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	10,03 €/MWh
4	10,00 €/MWh	5,00 €/MWh	81,13 €/MWh	0,00 €/MWh	10,08 €/MWh
5	10,00 €/MWh	5,00 €/MWh	52,74 €/MWh	0,00 €/MWh	10,65 €/MWh
6	10,00 €/MWh	5,00 €/MWh	72,36 €/MWh	0,00 €/MWh	17,61 €/MWh
7	10,00 €/MWh	5,00 €/MWh	94,41 €/MWh	7.880,00 €/MWh	669,46 €/MWh
8	10,00 €/MWh	5,00 €/MWh	95,18 €/MWh	7.880,00 €/MWh	1.631,05 €/MWh
9	10,00 €/MWh	5,00 €/MWh	92,04 €/MWh	7.880,00 €/MWh	692,67 €/MWh
10	10,00 €/MWh	5,00 €/MWh	93,65 €/MWh	0,00 €/MWh	6,45 €/MWh
11	10,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,25 €/MWh
12	0,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,03 €/MWh
13	0,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,03 €/MWh
14	0,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,03 €/MWh
15	0,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,03 €/MWh
16	0,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,03 €/MWh
17	0,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,04 €/MWh
18	10,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,10 €/MWh
19	10,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	5,85 €/MWh
20	10,00 €/MWh	5,00 €/MWh	0,00 €/MWh	0,00 €/MWh	7,62 €/MWh
21	10,00 €/MWh	5,00 €/MWh	88,20 €/MWh	7.880,00 €/MWh	103,83 €/MWh
22	10,00 €/MWh	5,00 €/MWh	95,18 €/MWh	7.880,00 €/MWh	959,11 €/MWh
23	10,00 €/MWh	5,00 €/MWh	95,18 €/MWh	7.880,00 €/MWh	1.069,53 €/MWh
24	10,00 €/MWh	5,00 €/MWh	95,18 €/MWh	7.880,00 €/MWh	962,76 €/MWh

Table 7: Average hourly cost per MWh for each technology

Lastly, the table chart offers a summary of the cost per MWh calculated on an hourly basis for each energy source. This tabular format serves as a quick reference for specific cost information and allows for easy comparison and analysis of the data. Providing a precise breakdown of the cost of producing a unit of electricity from each source over different hours, it captures the varying financial implications of using each energy source. As a tool, it complements the visual representation of the data.

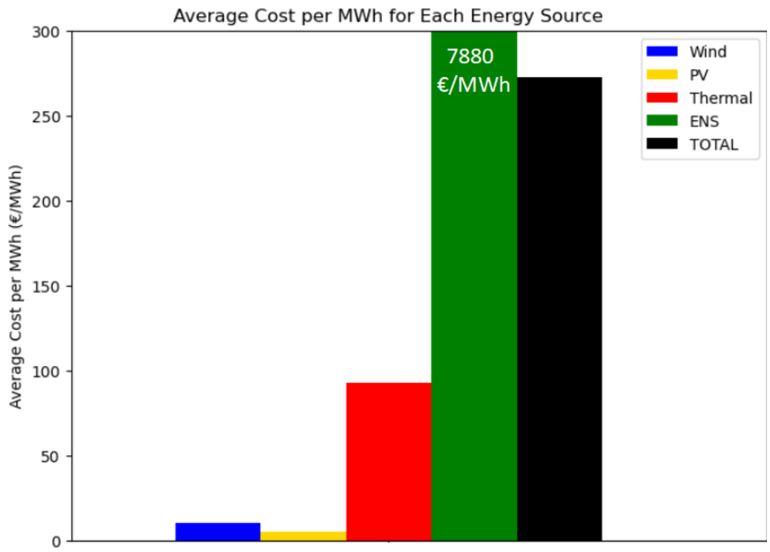

Figure 27: Overall average cost per MWh for each technology

The bar plot depicts the overall average cost per MWh values for each technology. It tells us what is the average cost that we need to pay for any technology for a produced unit of electrical generation. Due to certain time periods not fulfilling the demand, the total overall average cost per MWh is significantly higher than the overall average cost per MWh of any technology, including thermal.

	Total Energy Dispatched (MWh)	Total Cost (€)	Average Cost per MWh (€/MWh)
Wind	262.607,67	2.626.076,67	10,00
PV	272.902,97	1.364.514,84	5,00
Thermal	34.297,48	3.174.975,15	92,57
ENS	19.458,62	153.333.948,78	7.880,00
TOTAL	589.266,73	160.499.515,44	272,37

Table 8: Total generation, cost and overall average cost per MWh for each technology

The table presented offers a comprehensive overview of the key metrics in our analysis: total dispatched energy, total cost, and overall average cost per MWh for each technology. This detailed representation allows for quick comparison and straightforward interpretation of the data and serves us as an illustrative data presentation tool in our understanding of the economic dispatch energy system.

4.1.8 Short-term marginal costs

Marginal costs tell us about the expenses associated with the production of an additional unit of a commodity, in this case, a unit of electricity. Knowing the expense of producing additional unit of energy is a critical factor in deciding the quantity of electrical energy we want to generate and which source to utilize at any time. They play a significant role in long-term strategic decisions within the energy sector. Overall, they are an important concept in energy economics. They shape everything from daily operation decisions to long-term planning.

Figure 28: Short-term marginal cost

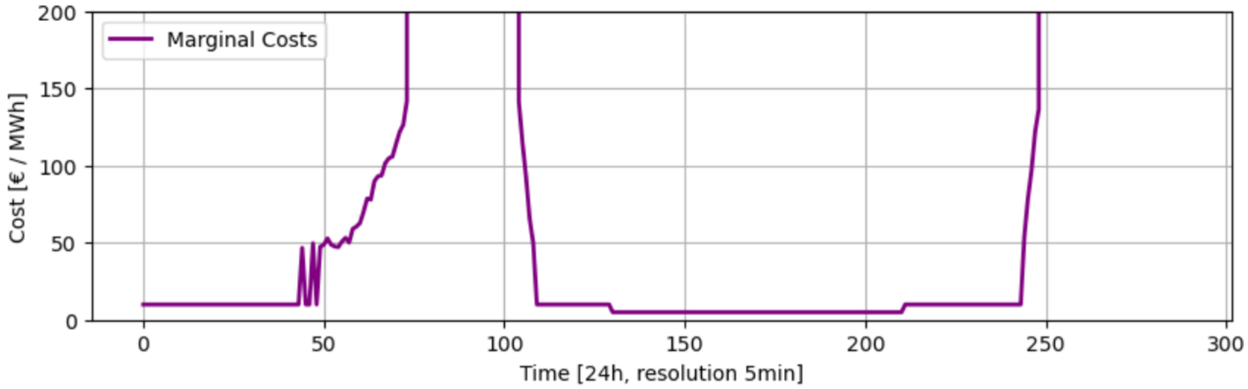

Figure 29: Short-term marginal cost in lower ranges

In our example, we showcase the value of marginal costs twice. The first chart shows the total marginal costs of the system, and the second shows closed-up values to better study the marginal costs when there are no periods of ENS. The graph's view of the marginal costs over time offers insights into how the cost of producing one additional unit of electricity varies within the day, providing a useful tool for understanding the economics of electricity production in the short term.

The charts that follow present two critical measures in understanding the financial dynamics of energy production: the average cost per MWh and the short-term marginal cost. Calculated over a 24-hour period and displayed in 5-minute intervals, these costs provide insight into the economic situation of our energy system.

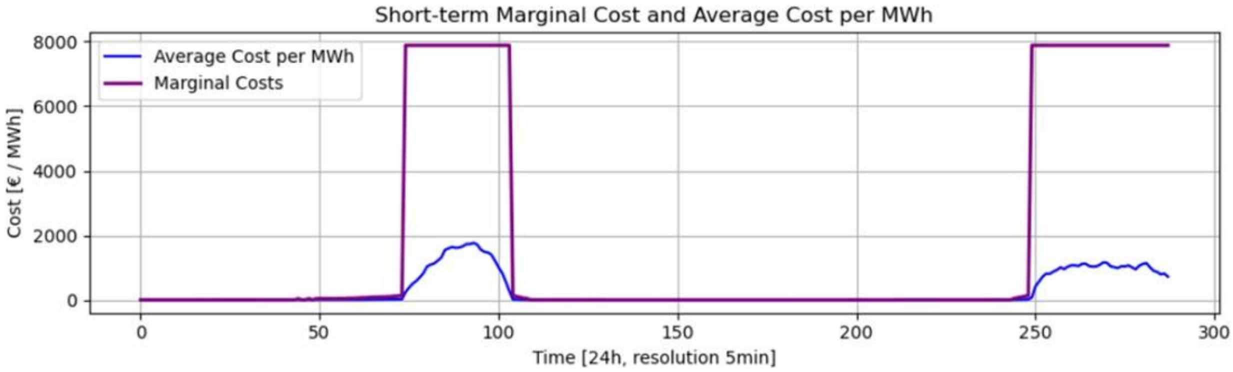

Figure 30: STMC and average cost per MWh

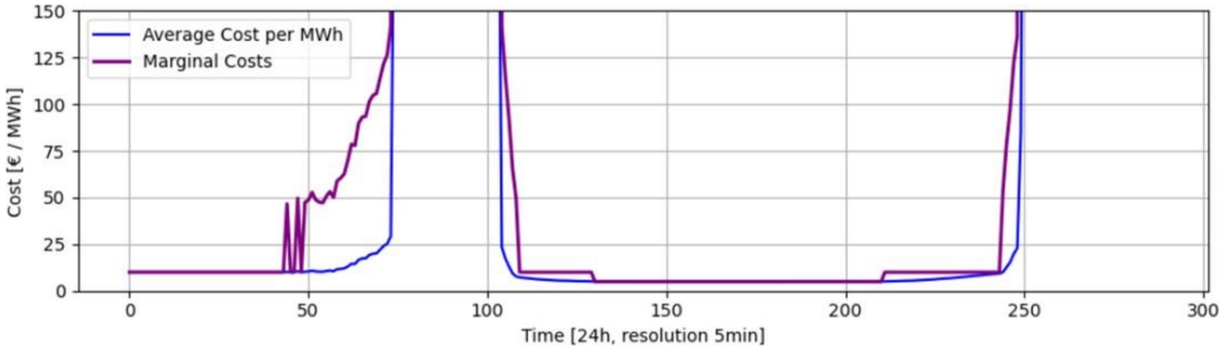

Figure 31:STMC and average cost per MWh in lower ranges

The first line in each plot, labeled as "Average Cost per MWh", shown in blue, represents the average cost of producing each MWh of energy. It conveys the required average cost for a MWh of energy generated across all generation technology domains at every time interval. The second line, displayed in purple, shows the previously mentioned marginal costs.

In a perfect scenario for energy production, power plants are put to work in the order of their marginal costs. This is known as the merit order. The merit order is a way of ranking available sources of energy, based on ascending order of price. In a centralized management, the ranking is so that those with the lowest marginal costs are the first ones to be brought online to meet demand, and the plants with the highest marginal costs are the last to be brought on line. Dispatching generation in this way minimizes the cost of production of electricity [25]. This is why the average cost is equal to or less than the marginal cost at any given time. The average cost is the same as the marginal cost when only wind generator is active at nighttime and when only solar generator is active during daytime. When the demand is not met during those times, the thermal generator and ENS get activated. In those cases, the marginal costs significantly surpass the average cost per MWh of the system.

The difference between these two lines in the plots offers interesting information. When the average and marginal costs are the same, it suggests that the energy system is operating at peak efficiency. When the marginal cost is higher than the average cost, it indicates that more expensive resources are being used to meet increased demand, because the cheapest source itself is unable to fulfill the demand.

4.2 Annual dispatch model

4.2.1 Dispatched values

The Annual Generation Dispatch charts offer a broader, year-round perspective on how each power source contributes to meeting Spain's annual energy demand. These charts track how much energy is generated by each source on a daily basis over the course of the year.

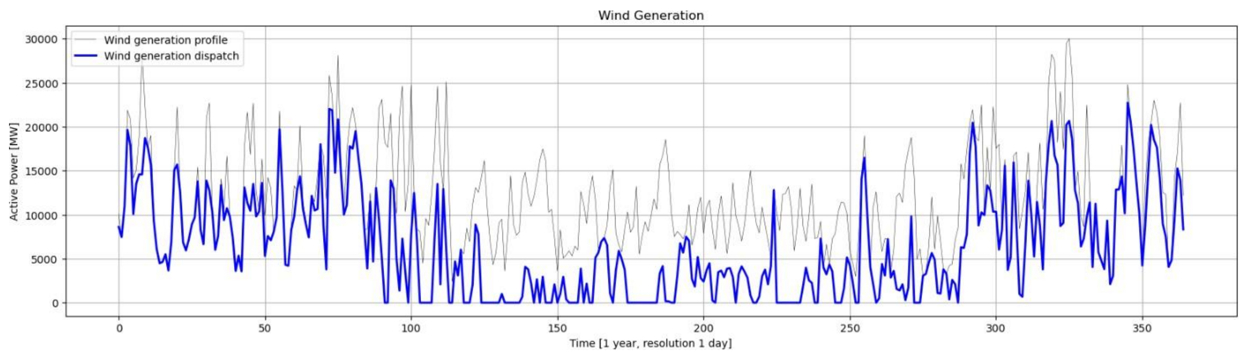

Figure 32: Wind dispatched annual generation

The wind energy dispatch chart presents an annual view of both the potential generation and the actual dispatch of wind power. This graph distinctly illustrates the inherent variability of wind energy. Furthermore, a diminished reliance on wind power during the summer months is clearly discernible, with some daily outputs even dropping to zero. This indicates that the total demand is satisfied by the more cost-effective solar production during these periods. However, such observations highlight the limitations of utilizing daily data, as it doesn't capture the details of hourly variations. This serves as a reminder of the constraints imposed by our chosen data of low granularity. We can conclude that the results are accurate, but in that case an energy storage technology implementation would be needed.

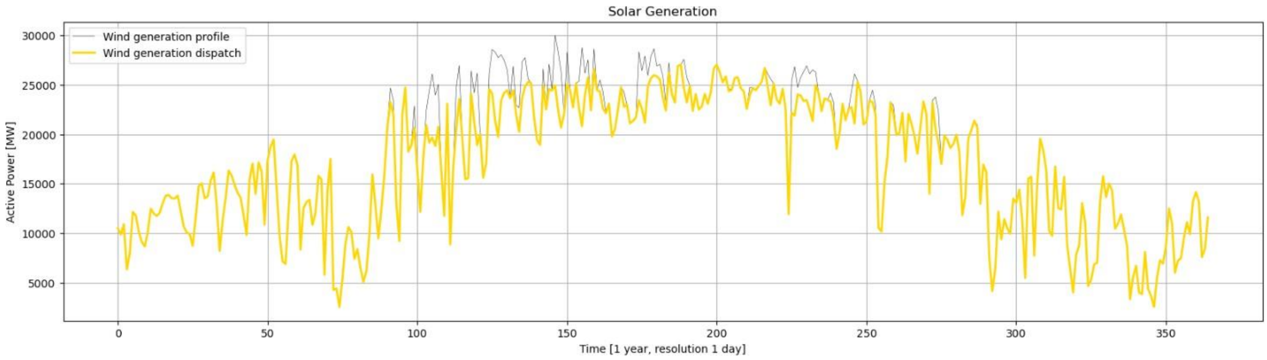

Figure 33: Solar dispatched annual generation

Similarly, the solar energy dispatch chart reflects the annual rhythm of solar power generation. The influence of seasonal and environmental factors can be observed. This graph also illustrates how the system tends to prioritize dispatching solar energy when available due to its lower costs compared to other sources.

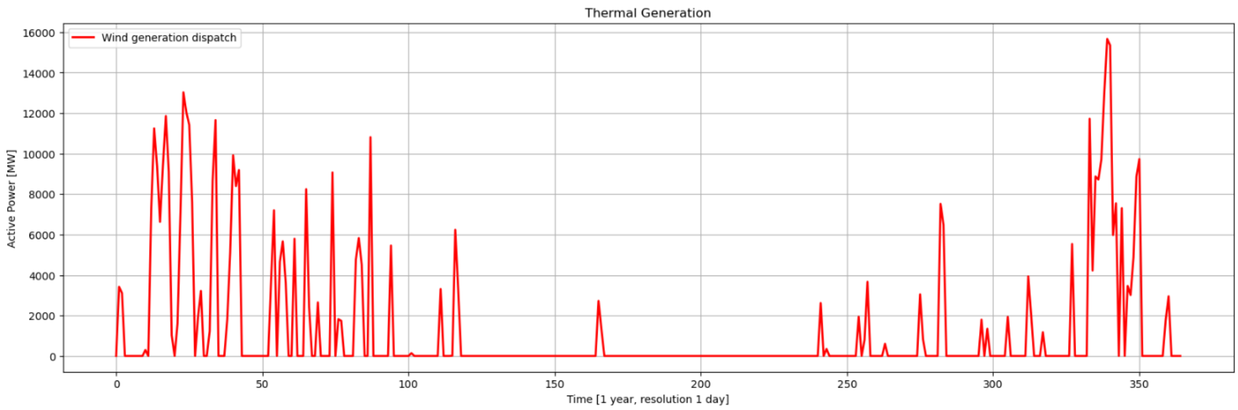

Figure 34: Thermal dispatched annual generation

Next, the thermal energy dispatch chart depicts the critical role of thermal power in the power system. Unlike renewable sources, thermal energy is dispatched to fill the gap when the combined output from wind and solar sources doesn't suffice. Even though thermal energy generation comes with higher operational costs, its importance in preserving the stability of the power system is undeniable. Interestingly, with the increase of thermal generation capacities to 30 GW in our annual model, no additional generation from ENS was necessary.

In summary, our analysis of the annual dispatch charts provides valuable insights into the practical aspects of energy generation and system management. The charts illustrate both the challenges and possibilities when blending inconsistent renewable energy sources like wind and solar with more stable, conventional sources such as thermal energy. Particularly, they highlight the importance of data granularity. For instance, we notice instances where the dispatched solar energy seems to fulfill the entire demand, a scenario which isn't practically feasible. This underlines the need for more detailed, higher-resolution data to achieve more accurate modeling or the implementation of a storage facility.

4.2.2 Generation curtailments

The annual curtailment charts offer a view of undispatched wind and solar power across a year, enhancing our understanding of unexploited energy generation potential. Such yearly data reveals seasonal patterns that daily data might miss, such as consistent high curtailment during specific months or seasons, indicating possible systemic issues.

As we see from the graphs, during times of the year when there are fewer sunny hours, almost all of the solar energy produced gets dispatched, while during summer months peaks in solar curtailments can be observed. This in turn, causes wind curtailments to be greater in summer, as solar energy is cheaper and thus gets dispatched before wind energy.

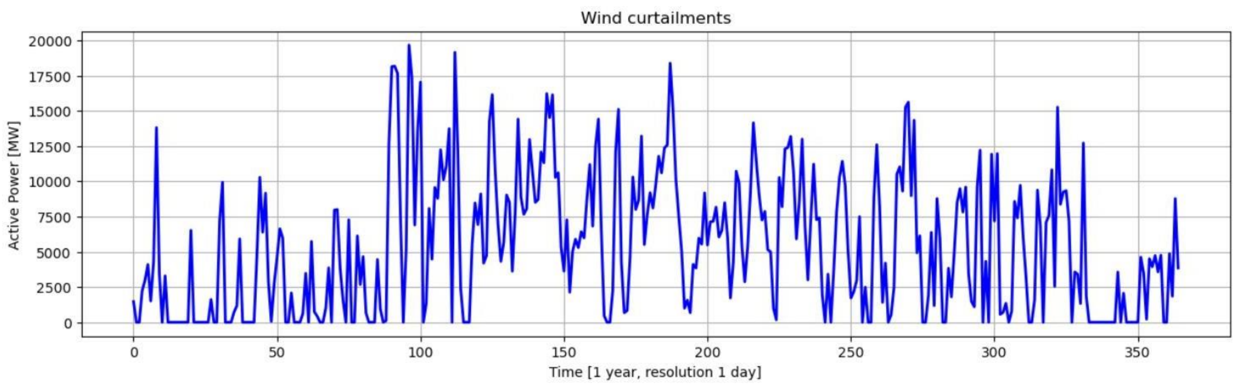

Figure 35: Wind annual curtailments

Despite this, wind curtailments are present throughout the entire year. We notice significant fluctuations in both energy sources, as wind power can vary greatly from one day to another, as well as clouds can obscure the sky, causing similar inequalities in solar energy production.

Annual Wind Curtailments [MWh]	Wind Annaul Dispatched Generation [MWh]
47.283.295,88	56.374.289,23

Table 9: Annual wind curtailments and dispatched generation

The table provides the data for annual wind curtailments, alongside the dispatched energy generation, for easy comparison of the two. Again, we can see that there is not much difference between the curtailment and dispatched generation values. This indicates that not much has changed from the daily model with respect to wind energy utilization efficiency.

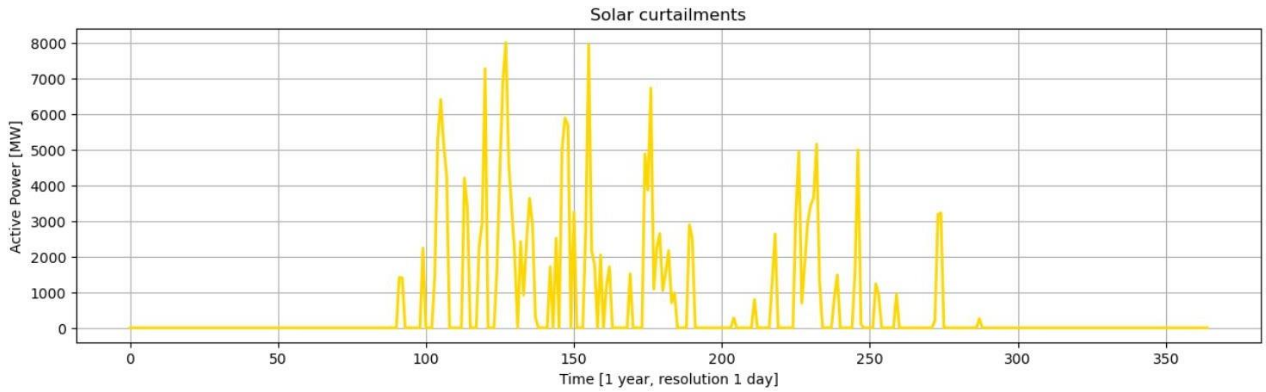

Figure 36: Solar annual curtailments

Annual Solar Curtailments [MWh]	Solar Annual Dispatched Generation [MWh]
5.316.593,44	148.124.214,65

Table 10: Annual solar curtailments and dispatched generation

The table illustrates the solar curtailments, as well as the total energy dispatch during the whole year. Once again, the dispatched generation is greatly superior to the curtailments, as solar generation dispatch gets prioritized over any other. We observe a similar dispatch to available generation ratio than in the daily economic dispatch model analysis.

As observed from the graphs, during periods of the year characterized by fewer daylight hours, a vast majority of the solar energy generated is dispatched. In contrast, during the summer months, peaks in solar curtailments are observed. This, in turn, leads to greater wind curtailments in the summer, as solar energy, being cheaper, gets dispatched before wind energy.

In terms of optimization, grid management, policy, and economic implications, annual curtailment data can inform long-term planning and decision-making. This aids us in identifying optimization opportunities, guiding grid upgrades, informing policy revisions, and shaping investment strategies. The goal is to reduce economic inefficiencies and promote renewable energy utilization.

4.2.3 Annual demand and curtailments comparison

The total demand curve illustrates the full extent of energy required daily throughout the year. The curve serves as the key metric of interest, with the aim of the energy system being to meet this demand consistently. Due to efficient management and the abundance of renewable resources, the Energy Not Supplied (ENS) value remains at zero throughout the year. This means that the total demand and total energy dispatched curves align perfectly, implying that the energy system has been able to satisfy all the energy demand at every point during the year.

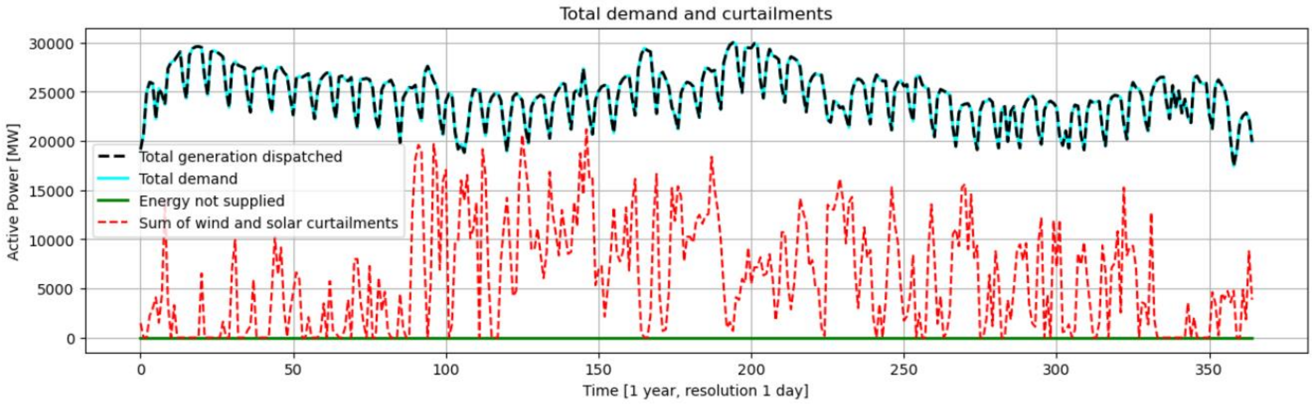

Figure 37: Total annual demand and curtailments

Notably, the curtailments never surpass the total energy demand at any point throughout the year. This indicates that the amount of unused potential from renewable energy sources is not excessively high, and that the system maintains a relatively balanced operation in terms of renewable energy production and consumption.

4.2.4 All power sources with total demand

The annual dispatch chart reveals how different energy-producing technologies contribute to meeting demand throughout the year.

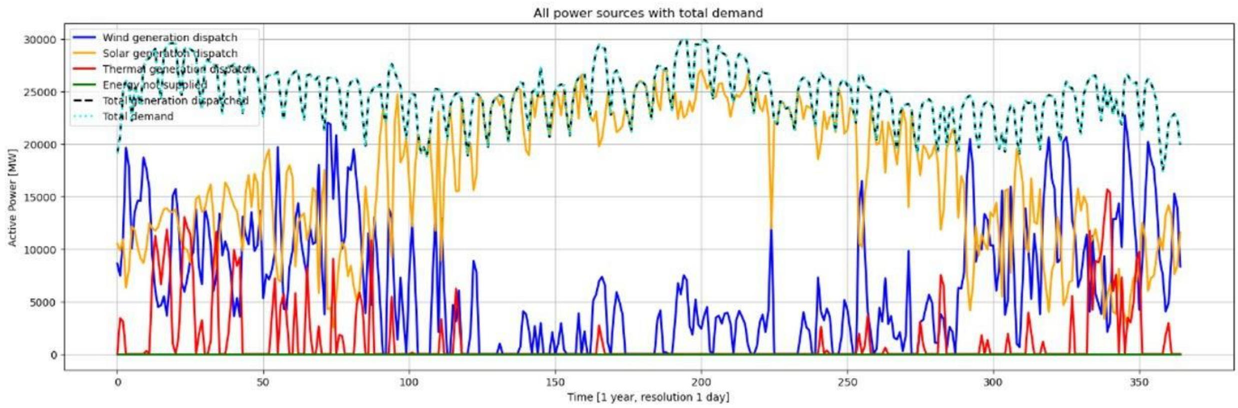

Figure 38: All power sources with total annual demand

Solar power production fluctuates with the seasons, peaking in the summer and diminishing in the winter. In contrast, wind energy maintains a more consistent output across the year, although its production still varies with weather conditions. During months when solar energy almost entirely covers the demand, the reliance on wind energy decreases. Thermal generation serves as a buffer during peak demand periods and when renewable sources are unable to meet demand. The absence of the ENS shows the system has enough capacity to fulfill energy demand all year round.

This chart helps us understand how these different energy sources work together to provide a constant supply, highlighting the importance of a diverse energy mix and showing potential areas for improved energy management.

4.2.5 Annual dispatch cost analysis

$$w_{cost} = v_W \times C_W \times 24$$

Equation 20: Wind generation annual cost

$$pv_{cost} = v_{pv} \times C_{PV} \times 24$$

Equation 21: Solar generation annual cost

$$th_{cost} = (900 + v_{th} \times 45 + v_{th}^2 \times 0.01) \times 24$$

Equation 22: Thermal generation annual cost

$$total_{cost} = w_{cost} + pv_{cost} + th_{cost}$$

Equation 23: Total generation annual cost

The calculations for wind and solar power costs involve multiplying the daily average power generation values *vw* and *vpv* with their respective costs per MWh: €10/MWh for wind and €5/MWh for solar, and then multiplying the product by 24, converting the values from megawatt-days to megawatt-hours. Similarly, thermal generation costs are computed, with the additional step of applying a quadratic function to represent its cost structure.

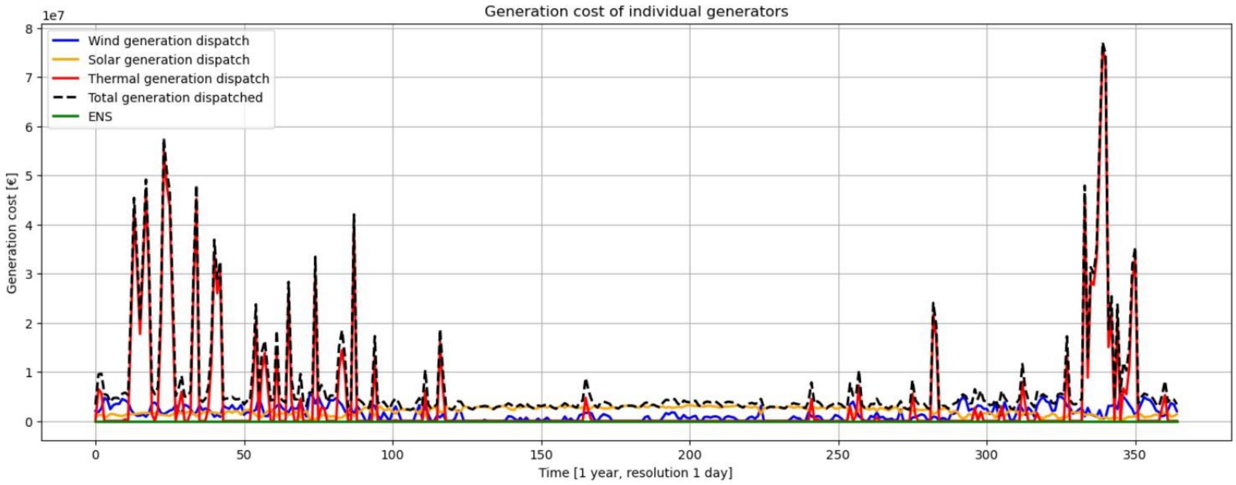

Figure 39: Generation cost of individual generators

The total cost graph reveals the cumulative cost obtained from energy dispatched by all three generators within each daily interval. This plot is particularly useful in providing a clear comparison of the costs associated with dispatching energy from different sources. It shows how these costs change over time. The total cost line provides a quick visual reference for the sum of costs from all sources. It is easily noticeable which days in the year find themselves in a renewable source energy production deficiency, as thermal energy is significantly more expensive than renewable wind and solar energy.

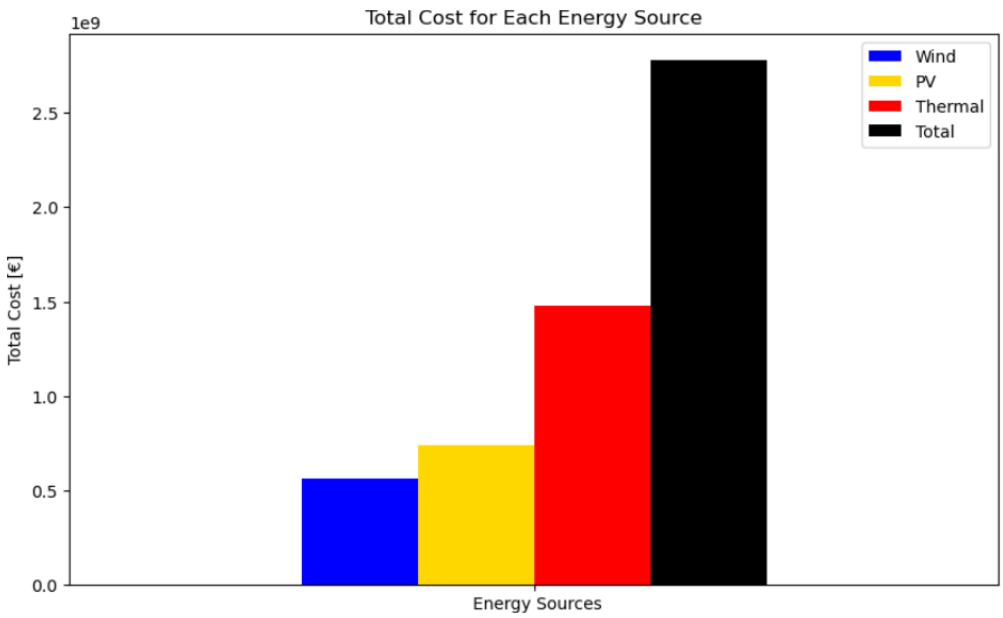

Figure 40: Total annual costs of individual generators

The total result bar chart presents the annual sum of dispatch costs for each of the power generation technologies. By merging the entire year's data into a single figure for each energy source, this chart offers a concise overview of the total annual costs associated with each technology. This perspective can provide valuable insight into the overall economic efficiency of different energy sources over the course of the year.

Wind	Solar	Thermal	Total
563.742.892,30 €	740.621.073,25 €	1.477.368.144,62 €	2.781.732.110,18 €

Table 11: Total annual dispatched production cost

The total result table chart builds on this by detailing the exact annual sum of dispatch costs for each energy source, as well as the total cost. Each cell contains the precise cost value for a specific energy type over the entire year. This simplified format makes direct comparison between the yearly costs of each energy source effortless, and quickly shows the costs of using different energy sources. From viewing the numeral data, it can be quickly realized that the thermal costs make up more than half of the total cost. Given that the goal of our project is to design a renewable and sustainable model, this data indicates that we might consider investing in greater capacities for the renewable energy sources to lower the short-term costs.

4.2.6 Costs per MWh

The annual charts displaying daily costs per MWh provide a comprehensive perspective on cost dynamics, accounting for every day within the year. These plots expose the varying costs over extended periods, offering insights into the long-term economic efficiency of each energy source. Two variations of these line charts are offered for a more detailed analysis.

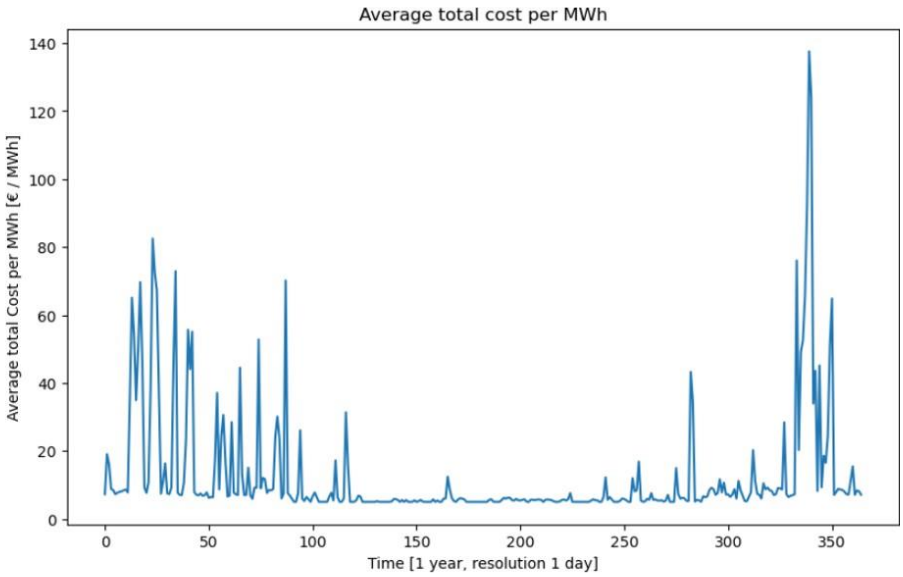

Figure 41: Average annual costs per MWh

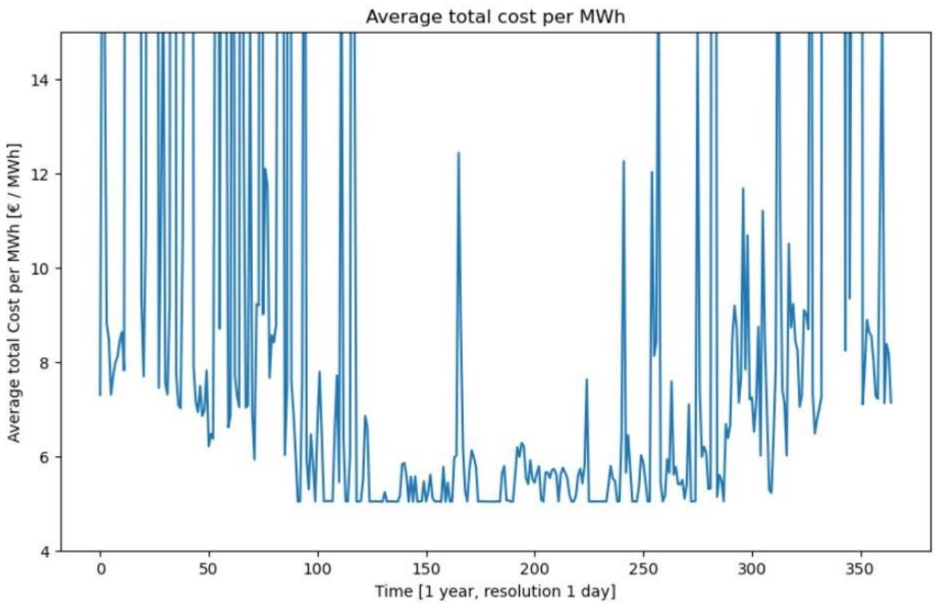

Figure 42: Average annual costs per MWh in lower ranges

Given the cost-efficiency of solar power, increased solar generation results in lower average costs per MWh during the summer months. Conversely, during the winter months when solar generation is reduced, we witness a rise in the average prices per MWh, reflecting the reliance on costlier sources of energy generation. Thus, the annual average cost per MWh showcases the influential role of seasonal changes in solar energy production on the overall economic efficiency of the power system.

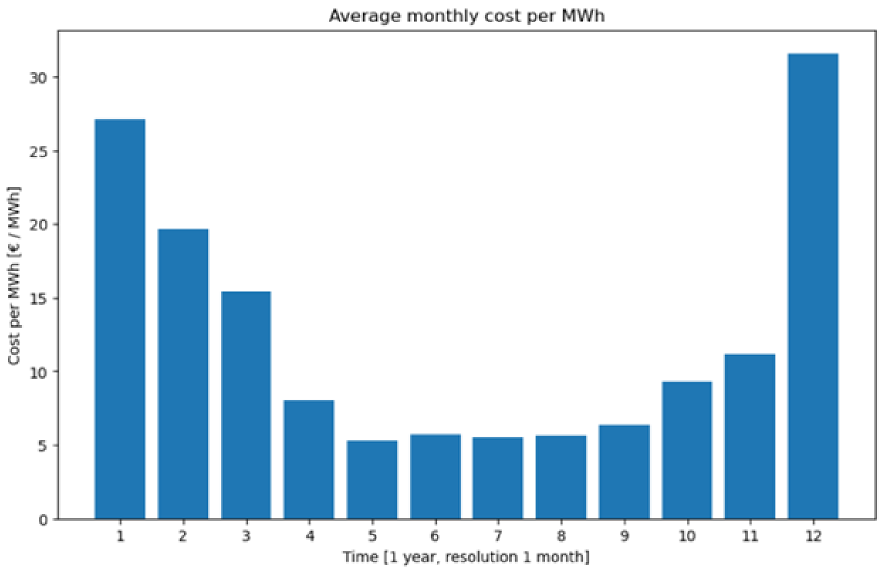

Figure 43: Average monthly costs per MWh

When these daily figures are averaged to yield monthly values, the bar chart displays a more consistent progression of costs over time. Averaging daily costs into monthly figures helps to neutralize day-to-day fluctuations, focusing instead on broader cost trends and seasonal patterns. This enables a comprehensive understanding of cost behavior, providing valuable data for refining energy generation schedules.

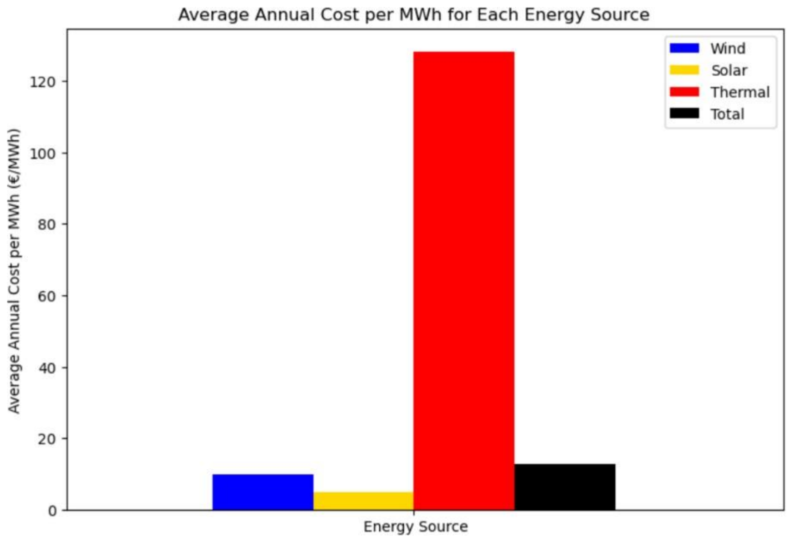

Figure 44: Average annual overall cost per MWh for each technology

The bar plot depicts the overall annual average cost per MWh values for each technology. It tells us what is the average cost that we need to pay for any technology for a produced unit of electrical generation. Unlike with the daily economic dispatch model, here we have no time periods of ENS, which significantly decreases the total average cost per MWh. The system is now much more sustainable from the short-term economic perspective.

	Total Annual Cost (€)	Total Annual Dispatched Generation (MWh)	Average Annual Cost per MWh (€/MWh)
Wind	563.742.892,30	56.374.289,23	10,00
Solar	740.621.073,25	148.124.214,65	5,00
Thermal	1.477.368.144,62	11.516.890,71	128,28
Total	2.781.732.110,18	216.015.394,59	12,88

Table 12: Total annual costs, generation and overall average costs per MWh for each technology

The table presented offers a comprehensive overview of the most important values in our analysis: total production cost, dispatched energy production, and overall average cost per MWh for each technology. This detailed representation allows for quick comparison and straightforward interpretation of the data and serves as an illustrative data presentation tool in our understanding of the economic dispatch energy system. Despite thermal generation contributing a comparatively lower amount of energy production, its inherently costlier structure leads to a significant increase in overall average cost per MWh of the system.

4.2.7 Annual short-term marginal costs

The annual view of the marginal costs offers a different perspective on these costs. By aggregating the data over a year, the annual marginal costs can illuminate the broader trends and patterns that may not be evident in the daily or monthly data. This temporal expansion provides a broader view of the cost landscape, illuminating the rhythms of the system's financial dynamics over a more extended period.

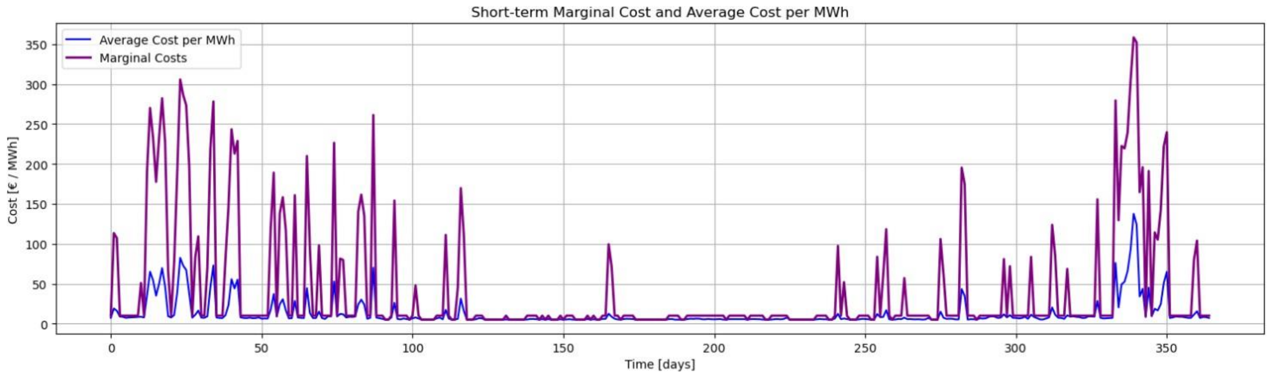

Figure 45: Annual STMC and average costs per MWh

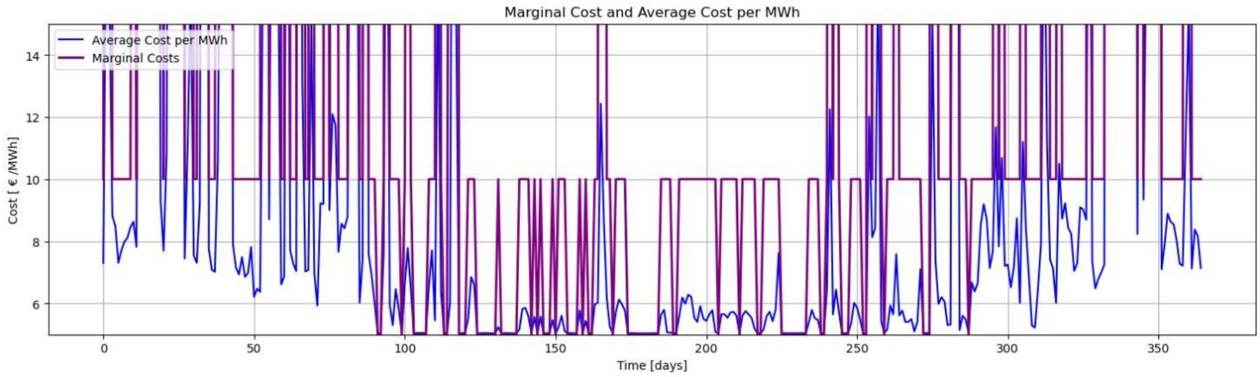

Figure 46: Annual STMC and average costs per MWh in lower ranges

Combining the annual average costs per MWh with the annual marginal costs in a single graph further enriches this perspective. This unified presentation highlights the correlation and disparities between these two key cost indicators across the whole year. As energy from the cheapest plants is produced first, the graph emphasizes the principle of the merit order in energy production, where the average cost consistently equals or stays below the marginal cost.

Especially in summer months, when renewable sources cover a larger share of demand, the gap between the two costs narrows, indicating an operation closer to peak efficiency. Thus, the unified presentation of these costs provides a comprehensive narrative of energy economics over the year, capturing both the general patterns and incremental changes in cost over the year.

4.3 Investment model

4.3.1 Dispached values

Planning how energy resources are distributed in power systems is an important step in reaching our project's objectives. This process involves constant adjustments to fulfill energy demand efficiently while considering the variability of renewable energy sources. To illustrate these operations, three charts are presented, each depicting the dispatch for a different energy source.

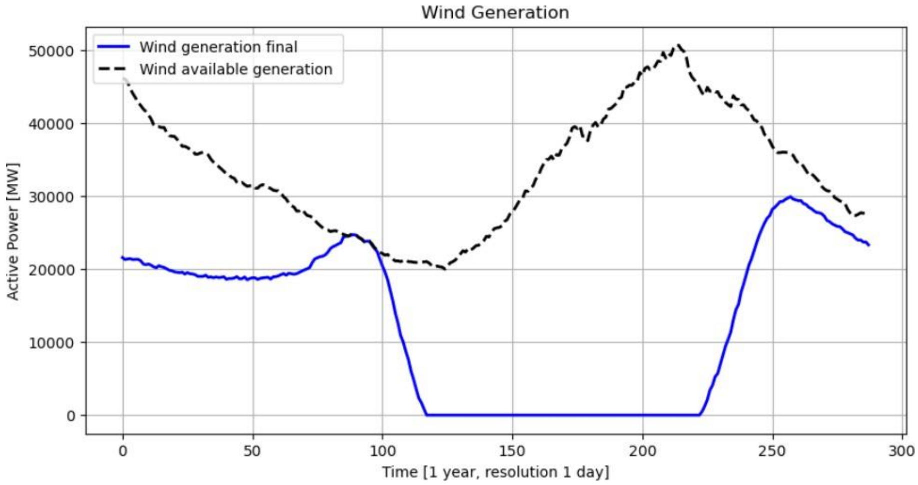

Figure 47: Wind dispatched investment generation

The wind energy dispatch chart provides the available wind power capacity as well as the actual wind power dispatched throughout the day. The graph illustrates the initial potential for wind power generation considering the newly invested capacity, which is noticeably greater than in the economic dispatch model. This is due to the model's capability to invest in additional wind generation units, thus increasing the maximum power output. The actual dispatched energy, after taking into account the demand and the dispatched energy from other sources, is also shown.

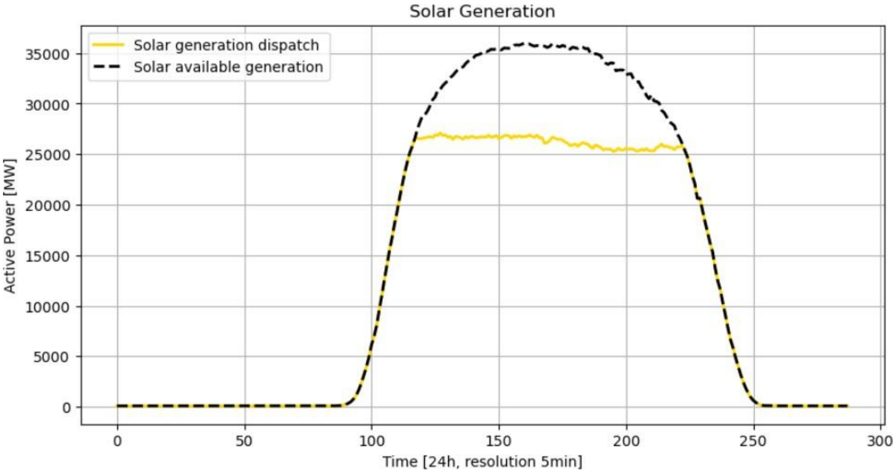

Figure 48: Solar dispatched investment generation

Similarly, the solar energy dispatch chart depicts both the potential and actual solar power generation. The impact of the investment model is clearly seen here as the capacity of solar generation has increased significantly compared to that in the economic dispatch model. This higher investment capacity enables the system to meet the energy demand solely through solar power for a large portion of the time, even while having some unutilized production capacity.

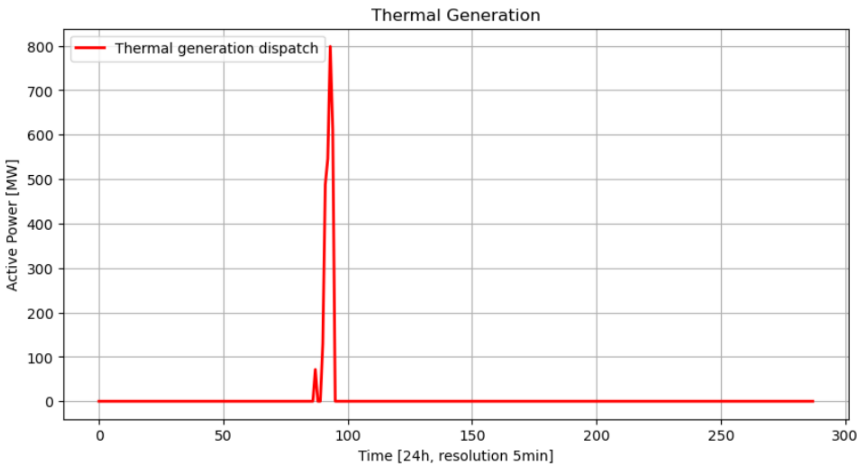

Figure 49: Thermal dispatched investment generation

The thermal energy dispatch chart presents the application of thermal energy in our system. Compared to renewable sources, thermal energy is dispatched only when the combined output from wind and solar fails to meet total demand, due to its higher operational costs. As observed from the graph, this only happens during a short period of time, as renewable sources cover all of the demand most of the time, thanks to new investment capacities.

The charts represent the dynamic nature of energy dispatch and the continuous adjustments required to balance supply and demand. However, unlike the economic dispatch model, in the investment model there are no instances of ENS. This is because the model allows for an increase in generation capacity, ensuring the demand is always met.

The primary difference between the economic dispatch model and the investment model lies in the additional capacity. The investment model is designed to consider future scenarios and invest in energy resources accordingly, which means it dispatches higher energy generation to meet total demand.

4.3.2 Generation curtailments

In the context of power generation, curtailments refer to the amount of power that could have been generated and dispatched into the grid but was not, due to various reasons such as grid constraints, lack of demand, or priority given to other sources of energy. Essentially, it's the gap between the potential and actual dispatched energy.

In our investment model, curtailments are also analyzed to provide insights into the energy dispatch strategy.

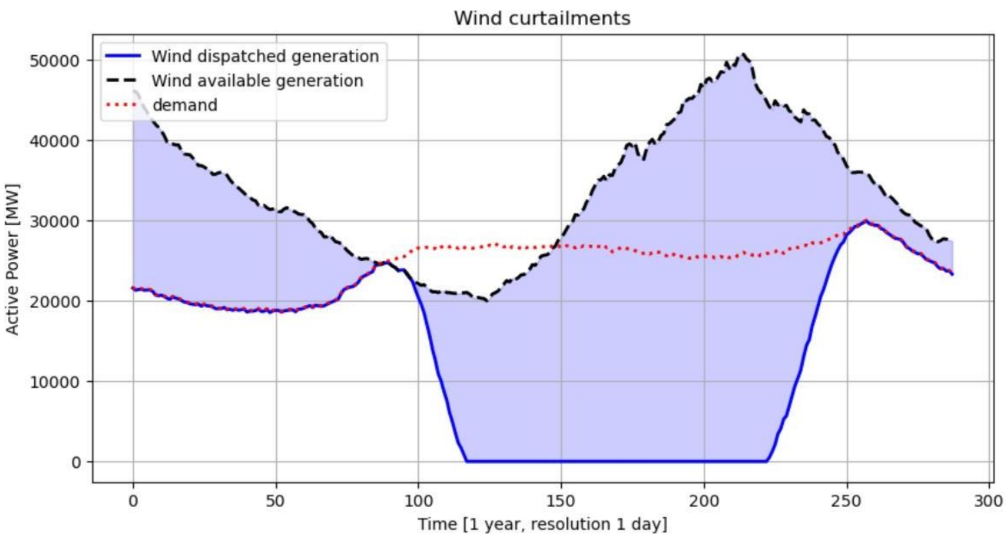

Figure 50: Wind curtailments

For wind power, the curtailments chart provides the difference between the initial wind power that could have been generated and the final wind power that was dispatched. Notably, the periods of wind curtailment coincide with times when the generated wind power alone exceeds the energy demand or when the solar energy source is prioritized.

Wind Curtailments [MWh]	Wind Dispatched Generation [MWh]
6.038.443,06	3.636.724,70

Table 13: Wind curtailments and dispatched energy

The table depicts the exact values of wind curtailments, as well as the wind dispatched generation. What quickly catches our attention is that the curtailments value is greater than the dispatched generation value. This happens due to increased investment capacities playing a pivotal role in synergy with the prioritization of the solar energy generation dispatch.

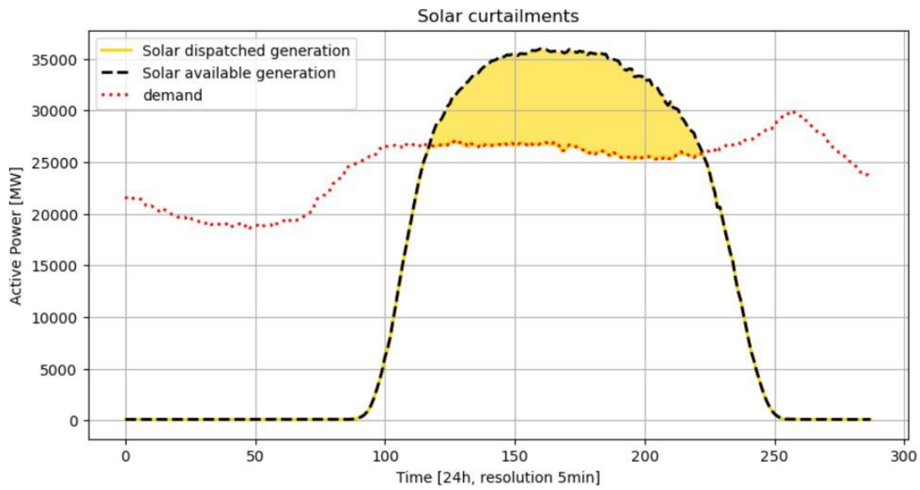

Figure 51: Solar curtailments

The solar curtailments chart displays the difference between the available and dispatched solar generation, which represents the solar curtailments. The areas of curtailment occur during the peak daylight hours when solar generation is active but not fully dispatched due to over-generation and lower demand.

Solar Curtailments [MWh]	Solar Dispatched Generation [MWh]
745.485,35	3.431.831,07

Table 14: Solar curtailments and dispatched generation

The table shows both the curtailments and dispatched generation values. In this case, the ratio between the two is superior in comparison to wind generation, mainly because solar power is cheaper to dispatch, thus it takes priority over wind power. From the results, we can also conclude that each of the renewable source generators covers roughly the same portion of the total demand.

4.3.3 All energy sources with total demand

Presenting the energy dispatch from wind, solar, and thermal energy sources alongside total demand in a single chart offers a holistic perspective on our energy system. It visualizes how diverse energy resources work together to fulfill the varying demand pattern throughout the day. Specifically, within the investment model, we can gain insights into how increased capacity investments influence the power dispatch from each source and impact the overall system dynamics.

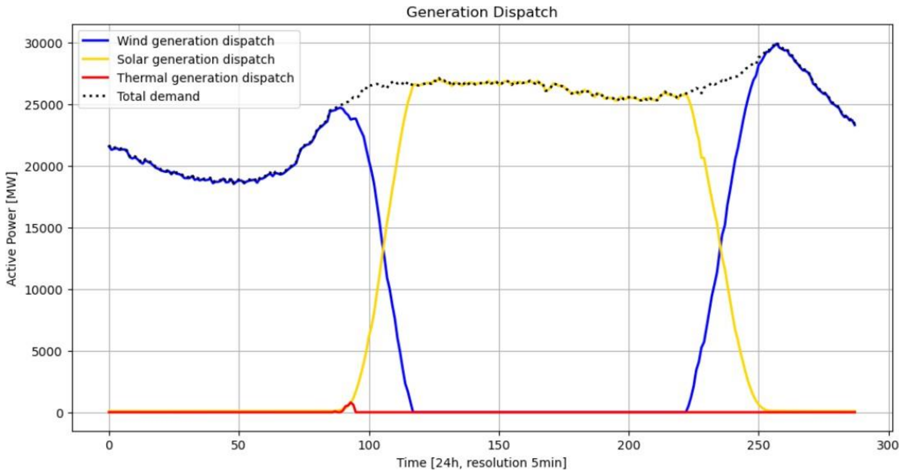

Figure 52: Dispatched investment generation of individual generators

As observed from the chart, the system significantly benefits from the increased investment capacities. It eliminates the need for energy not supplied (ENS), ensuring a reliable power supply for all of the demand. Importantly, the dependence on thermal energy is reduced, resulting in cheaper and cleaner energy production given the high operational costs and environmental footprint associated with thermal power generation. Increased reliance on renewable energy does not only minimize costs but also adds sustainability to our energy model. This combined visualization is useful for our understanding of the system, facilitating better and more cost-effective energy management decisions.

4.3.4 Average hourly dispatch production

Now, let's examine the average hourly power generation in the investment model. This view complements the previously presented line graph, as it averages the energy production per hour, smoothing out the variability in wind and solar generation.

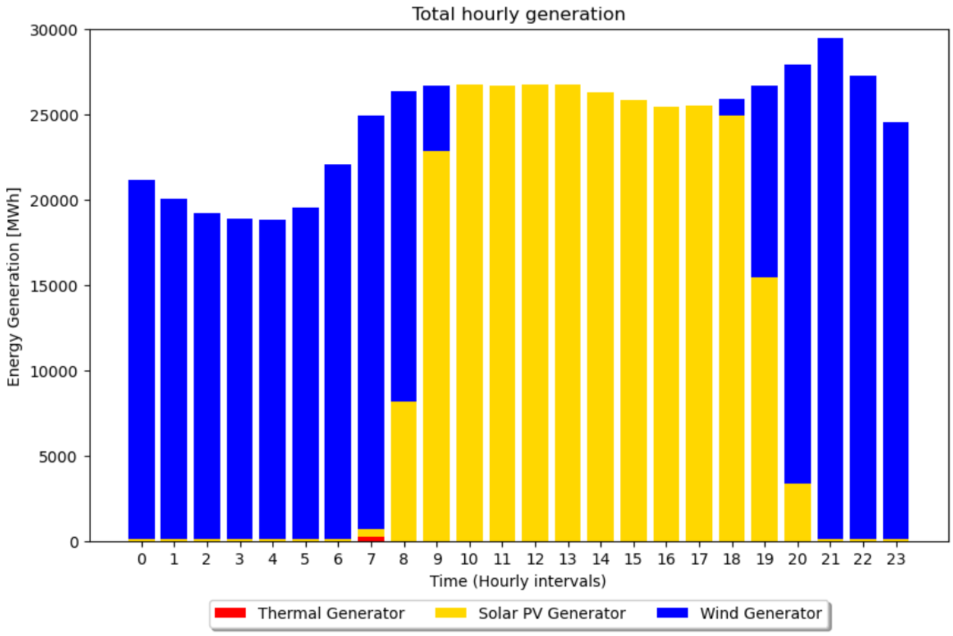

Figure 53: Total hourly dispatched generation

In examining the average hourly bar chart, the total energy produced at each hour throughout the day can be observed. The chart demonstrates that the demand is consistently met without the need for much unrenewable source energy utilization and with the complete absence of energy not supplied. The average hourly view of the total production dispatch can serve as a useful tool to determine the system's performance over a typical day. The graph format simplifies the data, rendering it easier to interpret the contribution of each source to total generation.

	Wind Production	Solar Production	Thermal Production	Total Production
1	21.097,05 MWh	85,44 MWh	0,00 MWh	21.182,49 MWh
2	19.938,09 MWh	85,84 MWh	0,00 MWh	20.023,93 MWh
3	19.116,19 MWh	85,64 MWh	0,00 MWh	19.201,83 MWh
4	18.784,21 MWh	85,64 MWh	0,00 MWh	18.869,85 MWh
5	18.753,88 MWh	84,44 MWh	0,00 MWh	18.838,32 MWh
6	19.443,92 MWh	84,44 MWh	0,00 MWh	19.528,36 MWh
7	22.009,31 MWh	84,44 MWh	0,00 MWh	22.093,75 MWh
8	24.218,08 MWh	450,01 MWh	220,42 MWh	24.888,51 MWh
9	18.206,17 MWh	8.147,83 MWh	0,00 MWh	26.354,00 MWh
10	3.806,70 MWh	22.857,35 MWh	0,00 MWh	26.664,05 MWh
11	0,00 MWh	26.768,98 MWh	0,00 MWh	26.768,98 MWh
12	0,00 MWh	26.646,12 MWh	0,00 MWh	26.646,12 MWh
13	0,00 MWh	26.726,80 MWh	0,00 MWh	26.726,80 MWh
14	0,00 MWh	26.741,76 MWh	0,00 MWh	26.741,76 MWh
15	0,00 MWh	26.265,89 MWh	0,00 MWh	26.265,89 MWh
16	0,00 MWh	25.832,11 MWh	0,00 MWh	25.832,11 MWh
17	0,00 MWh	25.460,11 MWh	0,00 MWh	25.460,11 MWh
18	0,00 MWh	25.509,01 MWh	0,00 MWh	25.509,01 MWh
19	945,57 MWh	24.915,10 MWh	0,00 MWh	25.860,68 MWh
20	11.220,67 MWh	15.434,66 MWh	0,00 MWh	26.655,33 MWh
21	24.554,47 MWh	3.345,77 MWh	0,00 MWh	27.900,25 MWh
22	29.328,75 MWh	118,86 MWh	0,00 MWh	29.447,61 MWh
23	27.171,30 MWh	85,64 MWh	0,00 MWh	27.256,94 MWh
24	24.466,01 MWh	84,04 MWh	0,00 MWh	24.550,05 MWh

Table 15: Total hourly dispatched generation

The table offers a more detailed look at these values, informing us of their exact numbers. Notably, wind and solar are generally the predominant sources, reflecting the investment strategy aimed at these renewable energies.

	Energy (MWh)
Total Wind Production	303.060,392
Total Solar Production	285.985,923
Total Thermal Production	220,421
Total Production	589.266,735

Table 16: Total dispatched generation

The table summarizes the total daily energy dispatched. The reduced reliance on thermal energy andthe absence of 'ENS' demonstrate the effectiveness of the investment model in balancing demand and supply while reducing costs and environmental impact. We can observe that renewable energy sources cover over 99,9% of the total demand. This observation signifies an important achievement within the investment model, where we have successfully transitioned to a predominantly cleaner and more sustainable energy system.

We can conclude that our investment model meets energy demand, predominantly through the efficient utilization of renewable energy sources. Our strategic investment in renewable wind and solar power accounts for almost all of the total demand, signifying a key achievement towards a cleaner, more sustainable energy system. This underlines the value of such strategic investments in ensuring a sustainable and cost-effective energy future.

4.3.5 Production cost analysis

A deep understanding of the costs associated with different energy sources is key to grasping the economic viability of our energy system. Let's now focus on how these costs are depicted in the investment model.

$$w_{cost} = v_w \times C_W \div 12$$

Equation 24: Wind production cost

$$pv_{cost} = v_{pv} \times C_{PV} \div 12$$

Equation 25: Solar production cost

$$th_{cost} = (900 + v_{th} \times 45 + v_{th}^2 \times 0.01) \div 12$$

Equation 26: Thermal production cost

$$total_{cost} = w_{cost} + pv_{cost} + th_{cost}$$

Equation 27: Total production cost

The above equations demonstrate how the production cost of the investment model is calculated. The cost of each energy source is calculated by multiplying the power production of the generator in each interval by the cost per MWh of that commodity. As we have 5-minute intervals, we have to divide the product by 12, to account for the difference in time scale. This step converts the units from 300 Megawatt-seconds (reflecting the 5-minute intervals) into Megawatt-hours. The cost of thermal power generation is calculated the following way: the base cost of 900 € is added to the price of multiplying energy production in each interval by 45 € / MWh with an additional term representing the square of thermal dispatch multiplied by 0.01 € / MWh^2. This represents non-linear cost elements associated with thermal power generation, such as efficiency losses at higher loads. The total equation is then divided by 12 to obtain the production cost value in every 5-minute interval. The final price consists of the sum of all the other prices.

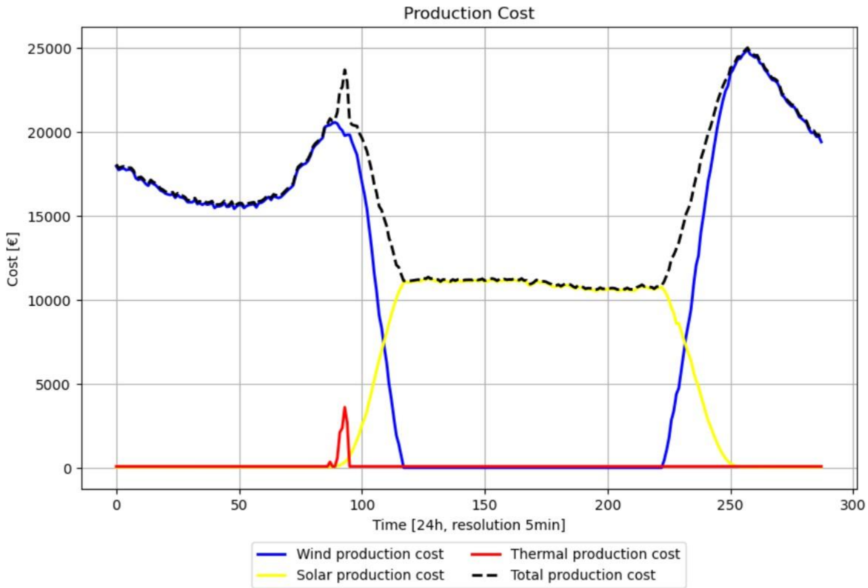

Figure 54: Production costs of individual generators

The graph illustrates the fluctuating costs tied to wind, solar, and thermal energy generation, represented in 5-minute intervals. This visualization assists in making clear comparisons between the costs of dispatching energy from various sources and how these costs evolve over time.

These costs are significant as they directly influence our investment strategies. In the investment model, we take into consideration these costs alongside the capital costs of installing new capacity. Hence, observing these trends can shape our decisions about where and when to invest in new capacity.

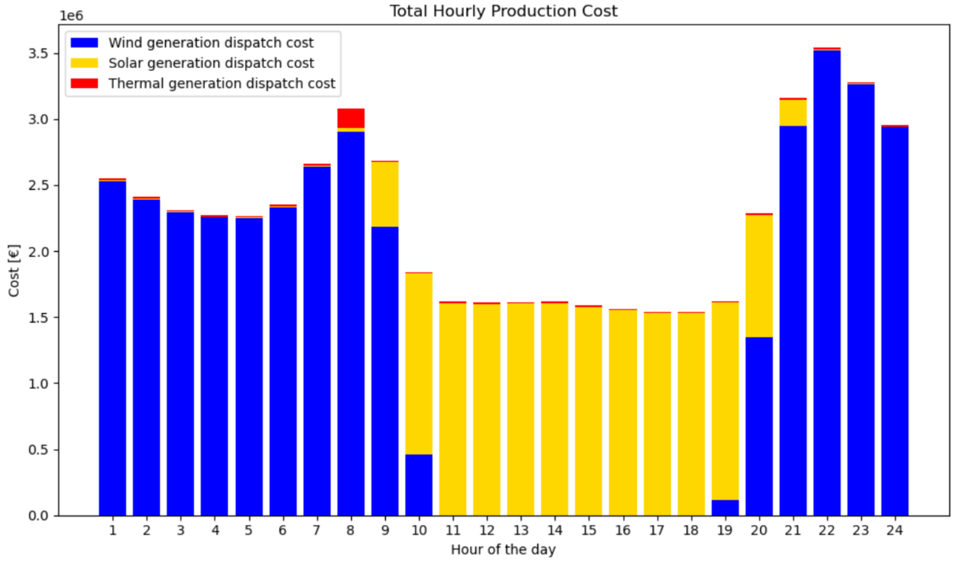

Figure 55: Total hourly production costs

Our bar charts and table chart offer a further breakdown of these costs. They present total dispatch cost in each hour for each of the power generation technologies. These visualizations are essential for pointing out cost disparities and identifying potential cost-saving opportunities. They help us understand cost dynamics throughout the day, which can guide operational decisions, such as adjusting dispatch strategies or scheduling maintenance.

	Generator	Total Cost
0	Wind	3.030.603,92 €
1	Solar	1.429.929,61 €
2	Thermal	32.826,79 €
3	Total	4.493.360,32 €

Table 17: Total production cost for each technology

Lastly, the table chart illustrates the total costs associated with each power generation technology. This overview is pivotal for financial planning and investment decisions. We can observe that, despite having a very slightly higher energy production, the cost of produced wind energy is more than double that of solar.

Overall, the detailed exploration of production costs provides essential insights into the operation and economic performance of our investment model. However, it's important to note that these production costs represent only one part of the total costs within this model. The other significant component includes investment costs, which are generally expected to be higher due to the capital required for establishing new generation capacity. In the next section, we will examine these investment costs to gain a better understanding of the economic aspects of the entirety of our energy system.

4.3.6 Investment cost analysis

To calculate the final investment cost for each generator, we first need to identify the investment cost per Megawatt-hour (MWh) for each specific technology. Once we have this information, we proceed by multiplying it by each generator's installed capacity to get the desired result.

There are two categories in which we can classify the costs of each generator. The first category is called Capital Expenditure (CAPEX) [26]. It is the cost of buying the equipment and installing it, along with the expenses that go with the process. The CAPEX for the photovoltaic, wind, and thermal technologies are 450.000, 900.000, and 730.000 euros per Kilowatt respectively.

However, these are not the only costs we must consider when discussing the investment model. We must also consider the concept that money available at the present time is worth more than the same amount in the future. This could be due to the investment possibilities that we can achieve with that money or inflation. Because of this, we use a financial function known as PMT (Payment). This is a financial function, which calculates the payment for a loan based on constant payments and a constant interest rate [27]. In our case, the PMT function to determine the yearly cost of our investment was a 6.5% interest rate with a 25-year lifespan of the generators.

As this is a daily investment model, we divided the annualized costs by 365. The calculation is presented in the following equations:

$$PMT(6.5\%, 25, 450000) \div 365 = C_{W}$$

Equation 28: Wind investment cost per MW_day

$$PMT(6.5\%, 25, 900000) \div 365 = C_{PV}$$

Equation 29: Solar investment cost per MW_day

$$PMT(6.5\%, 25, 730000) \div 365 = C_{TH}$$

Equation 30: Thermal investment cost per MW_day

The second category of costs is called Operational Expenditure (OPEX) [26]. This category encompasses the operational expenses of previously installed generators.

Calculating the investment costs thus involves considering both the initial capital expenditure and the operational expenditure (CAPEX and OPEX).

Wind investment cost per MW_day	Solar investment cost per MW_day	Thermal investment cost per MW_day
202,15 €	101,07 €	163,96 €

Table 18: Investment cost per MW_day for each technology

The table shows the obtained values following the calculations using financial function PMT. These costs are associated with establishing new capacities for energy generation.

$$w_{invcost} = C_{invW} \times i_{w}$$

Equation 31: Wind investment cost

$$pv_{invcost} = C_{invPV} \times i_{pv}$$

Equation 32: Solar investment cost

$$th_{invcost} = C_{invTH} \times i_{th}$$

Equation 33: Thermal investment cost

$$total_{invcost} = w_{invcost} + pv_{invcost} + th_{invcost}$$

Equation 34: Total investment cost

To calculate these costs, we multiply the investment cost per MWh by the capacity invested in each energy source.

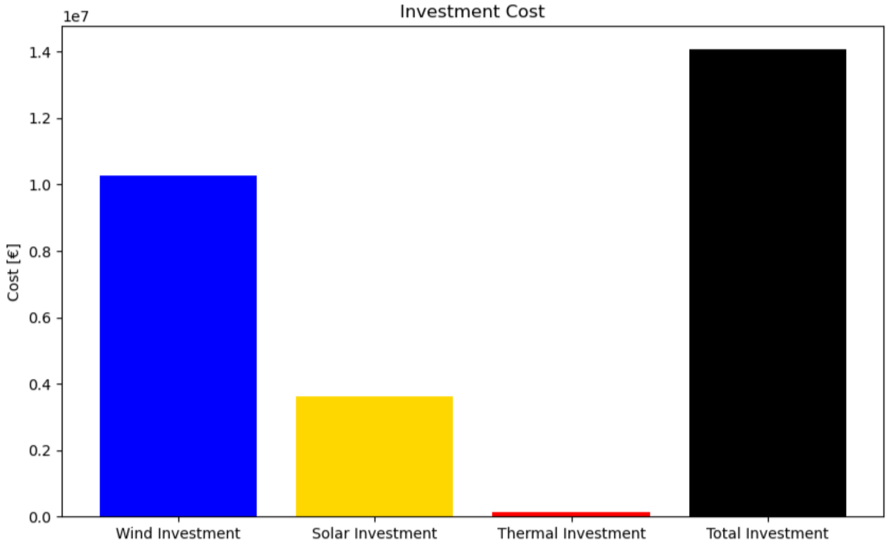

Figure 56: Investment costs of individual generators

The bar plot provides a visual representation of the investment costs. This plot breaks down the investment costs by type - wind, solar, and thermal - and also illustrates the total investment cost. It can be observed that wind investments cover more than two thirds of the total investment cost. Thermal investment, as expected fades in comparison with the investment of renewable sources.

Wind Investment	Solar Investment	Thermal Investment	Total Investment
10.238.868,93 €	3.635.378,21 €	130.923,30 €	14.005.170,44 €

Table 19: Total investment cost for each technology

Following the bar plot, a table chart is presented. This table offers the exact numerical values of the investment costs, further enhancing the precision and comprehension of the data. The investment costs for all energy sources are listed along with the total investment, allowing a straightforward comparison between the different costs.

4.3.7 Total cost analysis

So far the production and investment costs have been provided separately. By looking at them separately, we might overlook their combined impacts on the overall cost structure of the energy generation system. Thus, this chapter deals with the total cost, which is the sum of the production and investment costs.

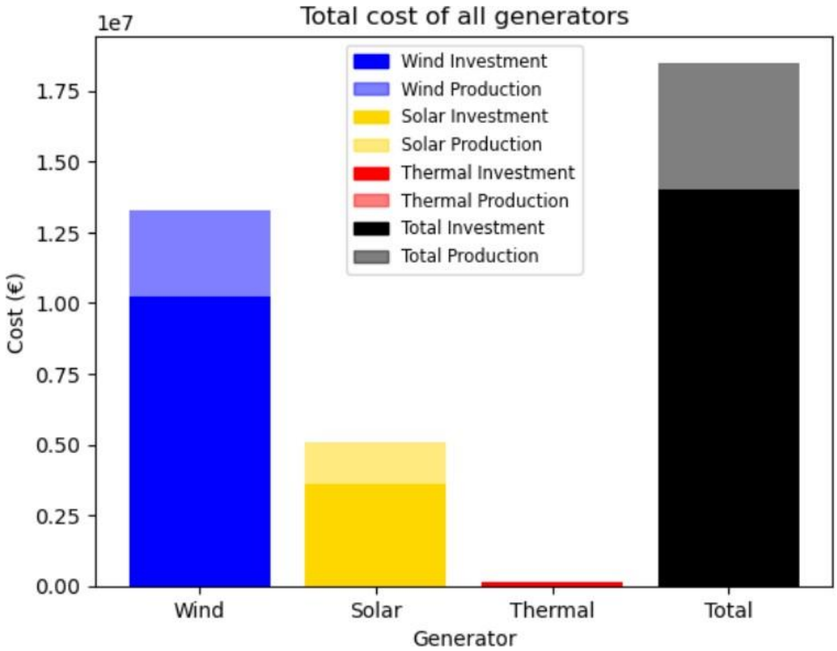

Figure 57: Total costs of individual generators

The bar chart depicts a holistic view of the total costs, which are split into two segments. Total cost of each generation technology is depicted, as well as the sum of all the total costs, which represents the production and investment costs of all generation technologies within the generation infrastructure. This visualization provides us with the proportions between the production and investment costs for each source, clearly showing to what degree investment costs go beyond production costs.

	Production cost [€]	Investment cost [€]	Total cost [€]
Wind	3.030.603,92	10.238.868,93	13.269.472,85
Solar	1.429.929,61	3.635.378,21	5.065.307,82
Thermal	32.826,79	130.923,30	163.750,09
Total	4.493.360,32	14.005.170,44	18.498.530,76

Table 20: Total cost for each technology

Following the bar chart, a tabular presentation of these same costs is provided. This table lists the individual production, investment, and total costs for each energy source, providing a concise and accurate summary of the results.

4.3.8 Production average costs per MWh

Next, the average total costs per MWh are depicted. This includes both the production costs and the investment costs of each generator. Thus, we form a comprehensive measure of the total cost per unit of electrical energy for each generator. This provides us with a complete understanding of the cost structure of the investment model in consideration.

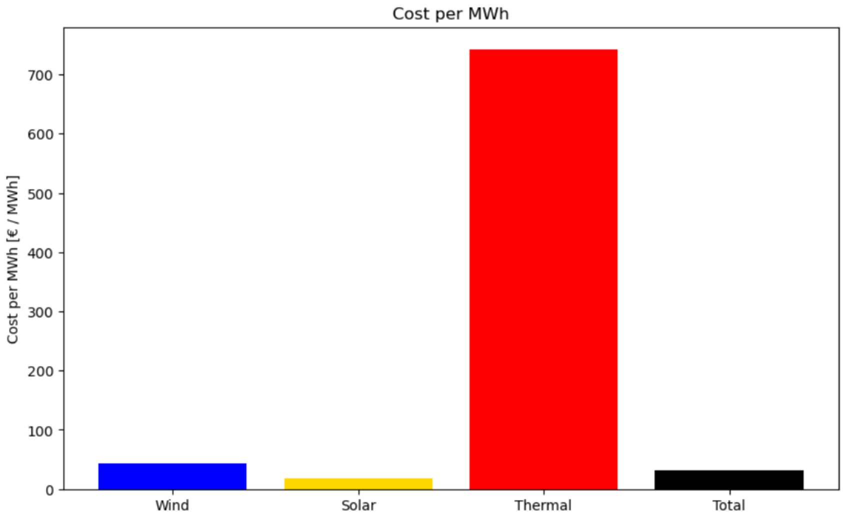

Figure 58: Average total costs per MWh

The bar plot visualizes average total costs per MWh, showcasing that thermal energy production greatly surpasses the renewable energy sources. Therefore, this graph shows promising results for the integration of renewable energy sources in the future. The financial viability of the photovoltaic solar generators looks especially profitable.

	Total cost [€]	Energy production [MWh]	Cost per MWh [€ / MWh]
Wind	13.269.472,85	303.060,39	43,78
Solar	5.065.307,82	285.985,92	17,71
Thermal	163.750,09	220,42	742,90
Total	18.498.530,76	589.266,73	31,39

Table 21: Total average cost per MWh for each technology

Adding to the information presented in the bar plot, the table chart gives us precise numerical values for the cost per MWh of each energy source. The table provides additional insight by showing not only the average cost per MWh for each energy source, but also their total energy production and total cost. This information provides an explanation for the dynamics behind the average total cost per MWh. Despite thermal energy having a significantly higher cost per MWh than the total cost per MWh of the system, when it comes to production, thermal generator's contribution to the total energy production is minuscule. As a result, the overall average cost per MWh does not get greatly affected by the thermal generator's high average cost.

In conclusion, looking at the average total cost per MWh is a crucial step in our cost analysis. It synthesizes both production and investment costs, giving us a holistic perspective of the financial situation for each energy source. This enables us to make well-informed decisions about our energy investment strategies.

4.3.9 Short-term marginal costs

In energy economics, short-term marginal costs (STMC) are vital in understanding the immediate costs related to scaling up energy production from different sources. These costs can provide valuable insights into efficient and informed decision-making on the operational level.

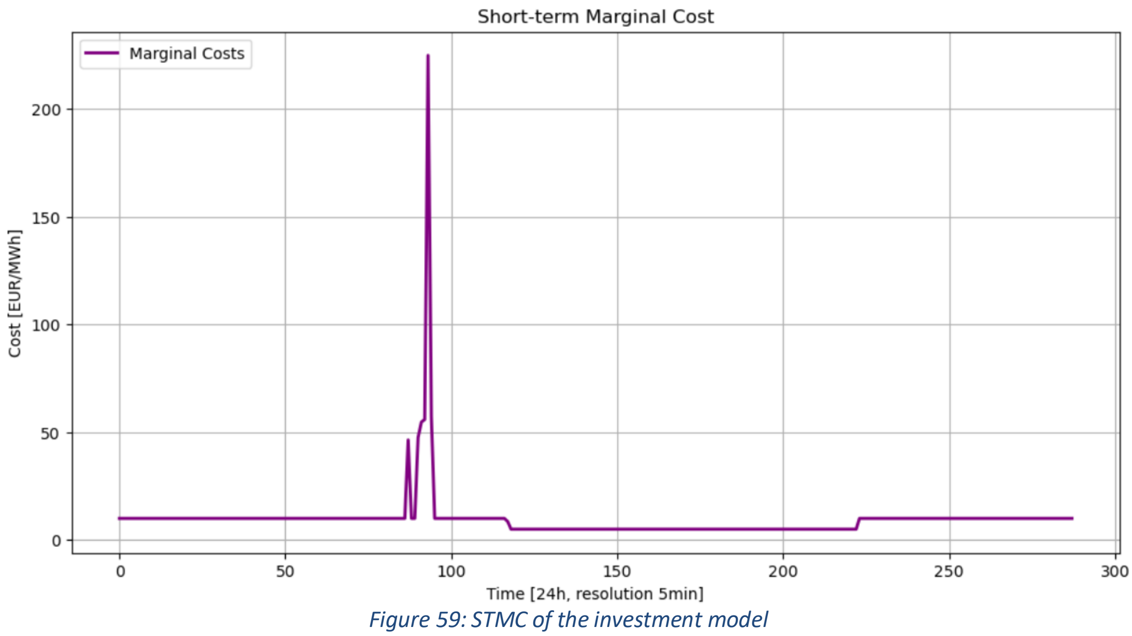

Figure 59: STMC of the investment model

The chart illustrates the STMC for our investment model. It is visible that during most of the time periods, the marginal cost of producing one extra MWh in the system's dispatch generation varies between 5 and 10 €. During a short period however, due to insufficient renewable capacities to cover the fullness of the demand, STMC rises up to 225 €. The graph's view of the marginal costs provides a useful tool for understanding the economics of electricity production of the investment model in the short term.

4.3.10 STMC and average production costs per MWh comparison

Our charts depict two key metrics essential for understanding the financial implications of energy production in our investment model. They are average production costs per MWh and short-term marginal costs. Captured over a day and demonstrated at five-minute intervals, these measures shed light on the daily cost fluctuations of our energy system.

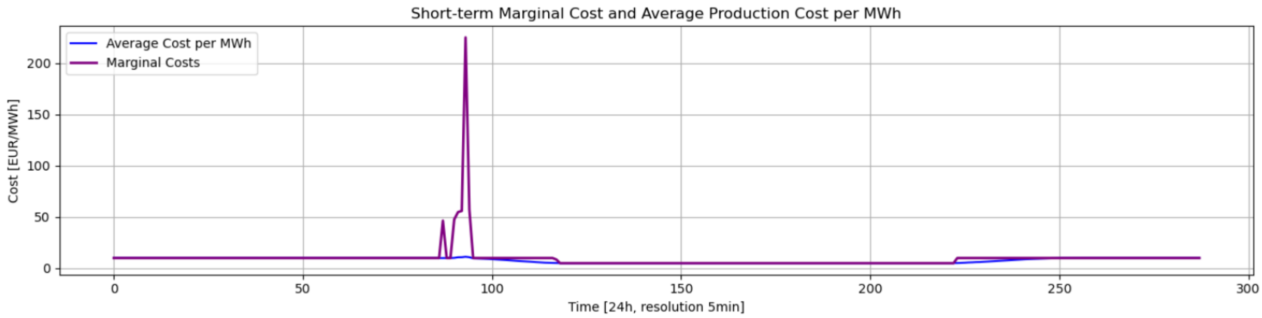

Figure 60: STMC and average production cost per MWh

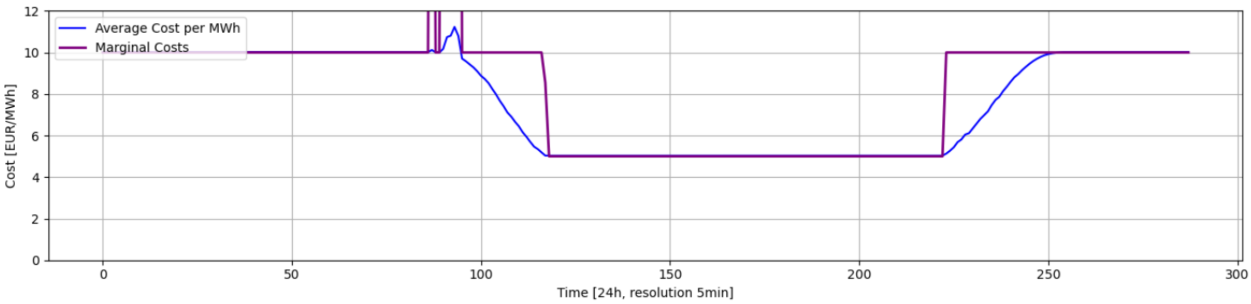

Figure 61: STMC and average production cost per MWh in lower ranges

Each plot portrays the average production cost per MWh and the short-term marginal costs - the cost of producing an extra unit of electricity. The system's aim is to follow the merit order - using power plants based on their marginal costs, starting from the least expensive ones. This pattern explains why average costs match or are lower than marginal costs at any moment.

When the two lines align our energy system operates at peak efficiency, optimally using all resources. On the other hand, when marginal costs exceed the average costs, it signals the usage of pricier resources to meet high demand, implying higher costs to produce additional energy. This happens in a short period of time in a cost-significant manner.

4.3.11 Investment viability

Investment viability refers to determining if the project is financially feasible or not. Investment viability is defined as whether an investment is (or has the potential to be) successful. A viable investment is profitable, which means it has more revenue coming in than it's spending on the costs of investing. If an investment isn't viable, it's difficult to recover. The investment would need to increase revenue, cut costs, or both. Viability is closely linked to profit as well as solvency and liquidity [28]. In the framework of this project, we compared the expected returns with the total costs, to determine if the investment was economically viable.

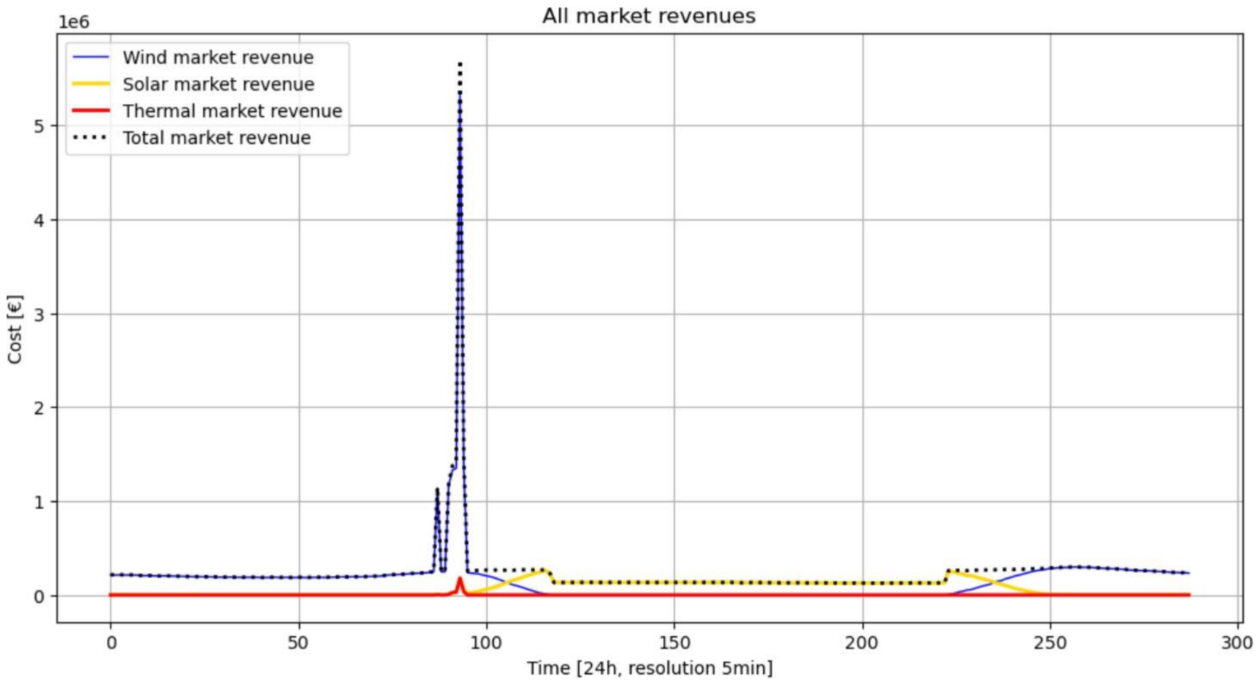

Figure 62: Market revenues of individual generators

The graph presents market revenues at each five-minute interval. Each data point in this graph represents the product of the market price and the amount of power produced during the corresponding interval. These values reflect the income potential at any given moment in the power market, offering insights into how fluctuating market prices and varying output levels can impact the overall profitability of the power plant.

Generation Technology	Market Revenue
Wind	46.606.115,94 €
Solar	20.794.533,57 €
Thermal	281.339,22 €
Total	67.681.988,73 €

Table 22: Market revenues for each technology

Following the graph, a table provides a summarized view of the total market revenues for each generator and the collective total. These numbers represent the culmination of income potential across the entire day. Moreover, the total revenue plays a key role in deciding if the calculated generation investments are economically viable. At the very minimum, this total amount should be enough to cover all the costs, both fixed and variable, to ensure the project canpay for itself.

	Production cost [€]	Investment cost [€]	Total cost [€]
Wind	3.030.603,92	10.238.868,93	13.269.472,85
Solar	1.429.929,61	3.635.378,21	5.065.307,82
Thermal	32.826,79	130.923,30	163.750,09
Total	4.493.360,32	14.005.170,44	18.498.530,76

Table 23: Production, investment and total cost for each technology

Upon examining the tables, it is clear that for each technology, market revenues exceed the total costs. This indicates a positive financial outcome in each case. Essentially, it means that the financial resources earned from selling the generated power are greater than the money spent on both creating and operating the generation facilities. This suggests that each technology has the potential to be not just operationally feasible but also financially profitable.

4.3.12 Long-term marginal costs

The concept of Long-term Marginal Costs (LTMC) plays an important role in understanding the economy of power generation systems. In the long run, no cost, not even capital cost, is fixed.

Consequently, the long-run marginal cost is found as the derivative of total costs, including investment, with respect to output [10]. This contrasts with Short-term Marginal Costs (STMC) which in a time span of minutes all normally considered production costs are fixed. When intervals of hours, days, months or up to a year are considered, variable costs change with the demand level, while fixed costs are unaltered during this time [10].

In the assessment of long-term energy production costs, we have to consider several key factors. One crucial aspect is the discount rate, here at 6.5%. This rate signifies the changing value of money over time. It's used to reduce future costs and benefits to today's values.

Another significant aspect is the lifespan of the generators. In our case we expect power generation equipment to last about 25 years. This span is of great importance when calculating the annuity factor, a ratio that translates the one-time investment cost into an equivalent annual cost. The annuity factor uses a formula that factors in both the discount rate and the generators' lifespan:

$$A_f = \frac{r \cdot (1+r)^n}{(1+r)^n - 1}$$

Equation 35: Annuity factor

$$A_{invcost} = A_f \times total_{invcost} \div C_f \times 365 \times 24$$

Equation 36: Annualized investment cost

In the equation *r* is the discount rate, while *n* is the lifetime of the generators. The result helps distribute the initial investment cost over the equipment's service years, giving a clearer understanding of its yearly financial effect.

The cost of investment and operation are further fundamental elements. Investment costs refer to the expenses related to building and installing a new power generation system, while operating costs pertain to the continual costs of maintaining and fueling the system. These costs differ depending on the generator and are vital when calculating the LTMC. For instance, the investment costs per MW for wind, solar, and thermal power generators are 900.000€, 450.000€, and 730.000€ respectively. In contrast, their respective operating costs per MWh are 5€; 1,25€; and

45,02€ [26].

The capacity factor is the ratio of the actual output over a period to its potential output if operating at full capacity continuously. It's a significant factor, with wind, solar, and thermal power generators having capacity factors of 0.5, 0.25, and 1, respectively [26].

The LTMC of each generator is determined by first spreading the initial investment cost across each year of the generator's life using an annuity factor. We then add the yearly operating costs and adjust for the generator's capacity factor to obtain a cost per unit of energy produced - €/MWh. This is done by dividing the annualized investment cost by the number of hours in a year, adjusted for the capacity factor. By accounting for the proportion of total energy each generator contributes, we find the overall LTMC.

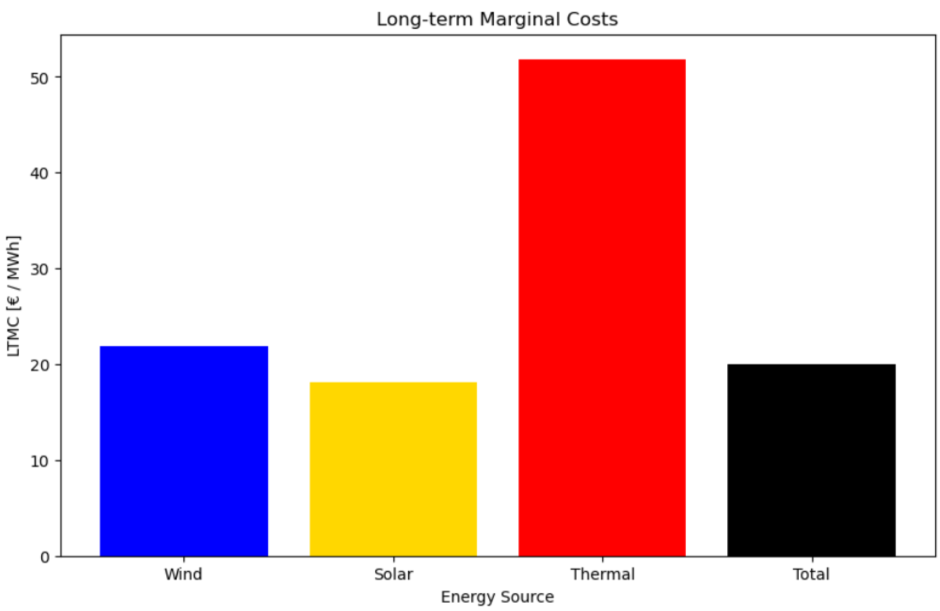

Figure 63: Long-term marginal costs for each technology

The bar chart presented showcases the LTMC for three sources of power generation. Each bar corresponds to the LTMC for a specific source, calculated based on the values mentioned above. The fourth bar represents the weighted average of all the long-term marginal costs, taking into consideration the proportion of total energy produced by each source.

Wind	Solar	Thermal	Total
21,85 € / MWh	18,10 € / MWh	51,85 € / MWh	20,04 € / MWh

Table 24: LTMC for each technology

The table provides the numerical values of the LTMC for every technology, as well as the weighted average of all the LTMCs. This data helps us to make better decisions about investing in different power generation technologies. The lower the LTMC, the more profitable the technology is over the long run. We can observe that out of all the technologies, solar generators have the lowest LTMC, making it the most profitable technology in our study. Wind follows closely. Alongside the thermal generators' disadvantages of having to use fuel, thus liberating greenhouse gas emissions into the atmosphere, their LTMC are also substantially greater than those of renewable sources.

In conclusion, the investment model has demonstrated a comprehensive view on the financial characteristics of energy production projects. It gives us the information about whether the project is worth investing in new capacities. With long-term marginal costs, the project's efficiency on the long-term is determined. We've made the case that from the point of view of long-term financial stability and ecological sustainability, we should strive towards an increasing reliance on renewable energy sources.

The analysis conducted within the scope of this project indicates a positive financial outcome. It's important to remember that our results pertain specifically to our data set. Therefore, in the future, various factors such as technological advancements or market dynamics could influence the results. Hence, it can be concluded that this model should always be reassessed to ensure that the results obtained are accurate in the ever-changing energy environment.

Chapter 5 Conclusion

In the end, this report explored the details of economic dispatch and investment problems. By doing so, focus was placed on three different models: daily and annual models of the economic dispatch, and the investment model for long-term planning. The main goal was to explore the most cost-effective methods of fulfilling the energy demand. The results of this study offer us valuable insights into the functionality and practicality of these models.

Findings of the daily economic dispatch model were valuable for their detailed analysis of evaluating and utilizing the data on 5-minute intervals. This enabled us to discern the hourly fluctuations in energy demand in great detail. These findings illustrated the balance between different sources of energy and their expenses. This enabled us to dispatch the most economically viable energy sources at any given interval. However, we've discovered that with the given generation capacities, we were not able to fulfill the fullnessof the demand at all times, which caused energy shortage in the periods of peak energy demands. This caused a huge increase in costs, due to scenarios of ENS. Another limitation of the daily dispatch model was its inability to provide an understanding of the system's operational capabilities over longer periods oftime.

Recognizing this, we introduced the model of annual economic energy dispatch. Besides increasing the time horizon, we also augmented the generator capacities to avoid previously discovered scenarios of power shortage. This enabled us to carry out a more conclusive study of energy economy dynamics. This approach allowed the system to optimize and dispatch all the necessary energy to cover the full scope of the demand throughout the entire year. We discovered that by expanding the time horizon of the study, we could better account for variations and patterns in demand and supply, which were not evident in dailyanalyses.

Adding the investment model provided an additional dimension to our study, focusing on the long-term impacts of capital decisions within the energy system. This model revealed a connection between capacity investment and the economic dispatch of energy production. We discovered that strategic investments incapacity could eliminate ENS within the daily dispatch model, even when operating under the same installed capacities. Evaluating the investment viability, we discovered that all the technologies under consideration were not only operationally feasible but also had the potential for financial profitability. This was evidenced by market revenues exceeding the total costs for each of these technologies. The long-term marginal costs offered valuable insights into the long-term efficiency of different technologies. The calculations proved the necessity of taking a long-term perspective when it comes to investment decisionsin the energy sector. By combining the short-term perspectives offered by the daily and annual dispatch models with the long-term view of the investment model, we've been able to provide a comprehensive analysis of the economic dispatch of energy generation.

In essence, with the use of three different models, we managed to find a balance between short-term operational needs and the long-term objectives. This led to a more reliable, sustainable, and cost-effective energy system. The acquired insights will serve as a roadmap for informing future operational and investment strategies. Different models help us comprehend the nuances of electrical energy production and distribution, revealing the intricate reality of the energy landscape through our research.

Resources

[1] Renewable Energy Market Update 2021 – Analysis – IEA: https://www.iea.org/reports/renewable-energy-market-update-2021

[2] LibreTexts Engineering - Economic Dispatch and Operations of Electric Utilities: https://eng.libretexts.org/Bookshelves/Environmental_Engineering_(Sustainability_and_Conservation)/Book%3A_Energy_Markets_Policy_and_Regulation/05%3A_Introduction_to_the_Electricity_Industry/5.06%3A_Economic_Dispatch_and_Operations_of_Electric_Utilities

[3] United Nations – Climate Action: https://www.un.org/en/climatechange/raising-ambition/renewable-energy

[4] ScienceDirect – Economic Dispatch https://www.sciencedirect.com/topics/engineering/economic-dispatch

[5] A new multiobjective procedure for solving nonconvex environmental/economic power dispatch: https://onlinelibrary.wiley.com/doi/10.1002/cplx.21505

[6] Multi-objective dynamic economic emission dispatch using particle swarm optimization variants: https://www.sciencedirect.com/science/article/abs/pii/S0925231217310767?via%3Dihub

[7] Evolving multi-objective neural networks using differential evolution for dynamic economic emission dispatch: https://www.semanticscholar.org/paper/Evolving-multi-objective-neural-networks-using-for-Mason-Duggan/143330e10fdd37f62ee7d8b3134b4ac99f90648f

[8] Energy-Investment Decision-Making for Industry: Quantitative and Qualitative Risks Integrated Analysis: https://www.mdpi.com/2071-1050/13/12/6977

[9] INTERNATIONAL ENERGY AGENCY - Lessons from Liberalized Electricity Markets: https://iea.blob.core.windows.net/assets/d0c52ee9-6f54-4735-81b2-6e0dd3ddbe13/LessonsNet.pdf

[10] Ignacio J. Pérez-Arriga (2013) – Regulation of the Power Sector

[11] SDG 7: Affordable and Clean Energy: https://sdgs.un.org/goals/goal7

[12] SDG 13: Climate Action: https://sdgs.un.org/goals/goal13

[13] United Power – Understanding Power Demand: https://www.unitedpower.com/demand

[14] Red Eléctrica de España (REE). Electricity system information: https://www.ree.es/en

[15] Datasheet for April 23rd, 2023: https://github.com/Lgams/Inputs

[16] Solar power in Spain: https://en.wikipedia.org/wiki/Solar_power_in_Spain#

[17] Rystad Energy - Spain's renewable power generation to top 50% in 2023, surpassing European neighbors on strong wind and solar capacity: https://www.rystadenergy.com/news/spain-s-renewable-power-generation-to-top-50-in-2023-surpassing-european-neighbor

[18] PV Tech - Spain to generate over 50% of power from renewables in 2023: https://www.pv-tech.org/spain-to-generate-over-50-of-power-from-renewables-in-2023/

[19] Iberdrola - Francisco Pizarro, the largest photovoltaic plant in Europe: https://www.iberdrola.com/about-us/what-we-do/solar-photovoltaic-energy/francisco-pizarro-photovoltaic-plant

[20] Evwind - Renewable Energy Innovations Transforming Spain's Energy Market: https://www.evwind.es/2023/06/17/renewable-energy-innovations-transforming-spains-energy-market/92282market/92282

[21] Spain | IEA Wind TCP - Wind Energy in Spain: https://iea-wind.org/about-iea-wind-tcp/members/spain/

[22] Global Factor - Spain presents the new National Integrated Energy and Climate Plan (PNIEC) 2023-2030: https://www.globalfactor.com/en/spain-presents-the-new-national-integrated-energy-and-climate-plan-pniec-2023-2030/

[23] Gurobi Optimization, LLC. (2021). Gurobi Optimizer. Retrieved from: https://www.gurobi.com/

[24] Datasheet for 2022: https://github.com/Lgams/Inputs/blob/main/Datos_2022.xlsx

[25] Merit order: https://en.wikipedia.org/wiki/Merit_order

[26] CAPEX and OPEX calculations excel sheet: https://github.com/Lgams/Inputs/blob/main/CAPEX_OPEX.xlsx

[27] Microsoft - PMT function: https://support.microsoft.com/en-us/office/pmt-function-0214da64-9a63-4996-bc20-214433fa6441

[28] What Is Business Viability: https://www.thebalancemoney.com/what-is-business-viability-3884327

Annex 1: Formulation

1. Libraries

```
#Reset
from IPython import get_ipython
get_ipython().run_line_magic('reset', '-sf')
```

```
#Gurobi Libraries
import gurobipy as gp
from gurobipy import GRB
import sys
#Other Libraries
import numpy as np
import pandas as pd
import csv
import math
#Libraries created
import importlib
#Libraries for excel import
import os
import xlwings as xw
import xlsxwriter
#Library for plotting timeseries results
import matplotlib.pyplot as plt
```

2. Input Data : Parameters

```
# Number of Generators
NG_TH = 1 #name updated
NG_PV = 1
NG_W = 1
#NG = NG_T + NG_PV + NG_W

# Number of Loads
ND = 1

# Number of periods
NT = 24*12 #time period

# Renewable Generators' Costs
C_PV= 5 #Cost of PV generation
C_W= 10 #Cost of WP generation

# Thermal Generators Cost
C_TH_parameters = np.array([[900, 45, 0.01]])
C_TH = pd.DataFrame(C_TH_parameters, index=["G1_T"], columns=["a", "b", "c"])

#Energy Not Supplied Cost
C_ENS= 7880

# Solar energy capacity
Q_PV = 30000   # Solar PV installed capacity (MW)

# Wind energy capacity
Q_W = 30000     # Wind installed capacity (MW)

# Thermal generator capacity
Q_TH = 5000 #name updated

#Demand max capacity
Q_D = 30000
```

3. Economic Dispatch Model using Gurobi

```
# CONSTRAINTS DEFINITION
 for t in range(NT):
     for g in range(NG_W):
         model.addConstr(v_w[g, t] <= QW_norm.iloc[g,t] * Q_W, name="Wind_Capacity_"+ str(g)+"_"+str(t))

 for t in range(NT):
     for g in range(NG_PV):
         model.addConstr(v_pv[g, t] <= QPV_norm.iloc[g,t] * Q_PV, name="PV_Capacity_"+str(g)+"_"+str(t))

 for t in range(NT):
     for g in range(NG_TH):
         model.addConstr(v_th[g, t] <= QTH_norm.iloc[g,t] * Q_TH, name="Thermal_Capacity_"+str(g)+"_"+str(t))

 for t in range(NT):
     model.addConstr(sum(v_w[g, t] for g in range(NG_W))  + sum(v_pv[g, t] for g in range(NG_PV)) + sum(v_th[g, t] for g in range(NG_TH)) + v_ens[:,t]
                     == sum(QD_norm.iloc[d,t] * Q_D for d in range(ND)), name="Power_Balance_" + str(t))


 # OBJECTIVE FUNCTION
 model.setObjective(sum(sum(C_W * v_w[g, t] for g in range(NG_W)) + sum(C_PV * v_pv[g, t] for g in range(NG_PV)) + sum(C_TH.iloc[g, 0] + C_TH.iloc[g, 1]
                           * v_th[g, t] + C_TH.iloc[g, 2] * v_th[g, t] * v_th[g, t] for g in range(NG_TH)) + C_ENS * v_ens[:,t] for t in range(NT)),GRB.MINIMIZE)
```

```
#Calculations after optimization
#Value of generation dispatch
v_w_df = pd.DataFrame(v_w.X, index=list(range(NG_W)), columns=list(range(NT)))
v_pv_df = pd.DataFrame(v_pv.X, index=list(range(NG_PV)), columns=list(range(NT)))
v_th_df = pd.DataFrame(v_th.X, index=list(range(NG_TH)), columns=list(range(NT)))
v_ens_df = pd.DataFrame(v_ens.X, index=["ENS"], columns=list(range(NT)))
#vPG_df = pd.concat([v_t_df, v_PV_df, v_W_df])

#Cost values
total_cost=model.objVal
w_cost= sum(sum(C_W * v_w.X[g, t] for g in range(NG_W)) for t in range(NT))
pv_cost= sum(sum(C_PV * v_pv.X[g, t] for g in range(NG_PV)) for t in range(NT))
th_cost= sum(sum((C_TH.iloc[g, 0] + C_TH.iloc[g, 1] * v_th.X[g, t] + C_TH.iloc[g, 2] * v_th.X[g, t] * v_th.X[g, t] for g in range(NG_TH))) for t in range(NT))
ens_cost= sum(C_ENS * v_ens.X[0,t] for t in range(NT))

#To compute marginal cost using the power balance constraint
marginal_costs=[]#initialization of a list to save the dual variables
for c in model.getConstrs(): #get all constraints of the model
    if ((c.ConstrName).startswith ("Power_Balance_")): #select only the constraints of power balance
        marginal_costs.append(c.Pi) #Add only dual variables of power balance constraint in margina_cost
marginal_costs_df = pd.DataFrame(marginal_costs)#marginal cost in dataframe format
```

Investment model

18. Investment Model using Gurobi

```
def investment_optimization_model2(ND, NG_W, NG_PV, NG_TH, NT, C_W, C_PV, C_TH, C_ENS, QD_norm, QW_norm, QPV_norm, QTH_norm, Q_D, C_inv_W, C_inv_PV, C_inv_TH):


    model = gp.Model("Investment_model")
    model.setParam(GRB.Param.MIPGap, 0.00001)

    v_w = model.addMVar(shape=(NG_W, NT), lb=0, vtype=GRB.CONTINUOUS, name="v_w")
    v_pv = model.addMVar(shape=(NG_PV, NT), lb=0,  vtype=GRB.CONTINUOUS, name="v_pv")
    v_th = model.addMVar(shape=(NG_TH, NT), lb=0, vtype=GRB.CONTINUOUS, name="v_th")
    v_ens = model.addMVar(shape=(1,NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="v_ens")

    #new decision variables
    i_w = model.addVar(lb=0, vtype=GRB.CONTINUOUS, name="i_w")
    i_pv = model.addVar(lb=0, vtype=GRB.CONTINUOUS, name="i_pv")
    i_th = model.addVar(lb=0, vtype=GRB.CONTINUOUS, name="i_th")
    q_dd = model.addVar(lb=0, vtype=GRB.CONTINUOUS, name="q_dd")


    #constraints
    for t in range(NT):
        for g in range(NG_W):
            model.addConstr(v_w[g, t] <= QW_norm.iloc[g,t]*i_w, name="Wind_Capacity_"+ str(g)+"_"+str(t))
        for g in range(NG_PV):
            model.addConstr(v_pv[g, t] <= QPV_norm.iloc[g,t]*i_pv, name="PV_Capacity_"+str(g)+"_"+str(t))
        for g in range(NG_TH):
            model.addConstr(v_th[g, t] <= QTH_norm.iloc[g,t]*i_th, name="Thermal_Capacity_"+str(g)+"_"+str(t))

    print(C_inv_W)
    for t in range(NT):
        #model.addConstr(sum(v_w[g, t] for g in range(NG_W)) + sum(v_pv[g, t] for g in range(NG_PV)) + sum(v_th[g, t] for g in range(NG_TH)) + v_ens[:,t] == sum(QD_norm.iloc[d,t] * Q_D for d in range(ND)), name="Power_Balance_" + str(t))
        model.addConstr(sum(v_w[g, t] for g in range(NG_W)) + sum(v_pv[g, t] for g in range(NG_PV)) + sum(v_th[g, t] for g in range(NG_TH)) + v_ens[:,t] == sum(QD_norm.iloc[d,t] * q_dd for d in range(ND)), name="Power_Balance_" + str(t))
        model.addConstr(q_dd == Q_D, name="Demand")


    model.setObjective(sum(sum(C_W * v_w[g, t] for g in range(NG_W)) + sum(C_PV * v_pv[g, t] for g in range(NG_PV)) + sum(C_TH.iloc[g, 0] + C_TH.iloc[g, 1] * v_th[g, t] + C_TH.iloc[g, 2] * v_th[g, t] * v_th[g, t] for g in range(NG_TH))
                       + C_inv_W * i_w  + C_inv_PV * i_pv  + C_inv_TH * i_th
                       ,GRB.MINIMIZE)


    model.optimize()
    model.write('Investment_Model.lp')

    Obj_value = model.objVal

    v_w_df = pd.DataFrame(v_w.X, index=list(range(NG_W)), columns=list(range(NT)))
    v_pv_df = pd.DataFrame(v_pv.X, index=list(range(NG_PV)), columns=list(range(NT)))
    v_th_df = pd.DataFrame(v_th.X, index=list(range(NG_TH)), columns=list(range(NT)))
    v_ens_df = pd.DataFrame(v_ens.X, index=["ENS"], columns=list(range(NT)))


    total_cost = model.objVal
    w_cost= sum(sum(C_W * v_w.X[g, t] for g in range(NG_W)) for t in range(NT)) + C_inv_W * i_w.X
    pv_cost= sum(sum(C_PV * v_pv.X[g, t] for g in range(NG_PV)) for t in range(NT)) + C_inv_PV * i_pv.X
    th_cost= sum(sum((C_TH.iloc[g, 0] + C_TH.iloc[g, 1] * v_th.X[g, t] + C_TH.iloc[g, 2] * v_th.X[g, t] * v_th.X[g, t] for g in range(NG_TH))) for t in range(NT)) + C_inv_TH * i_th.X
    ens_cost= sum(C_ENS * v_ens.X[0,t] for t in range(NT))

    marginal_costs=[]
    for c in model.getConstrs():
        if ((c.ConstrName).startswith ("Power_Balance_")):
            marginal_costs.append(c.Pi)
    marginal_costs_df = pd.DataFrame(marginal_costs)

    marginal_costs2=[]
    for c in model.getConstrs():
        if ((c.ConstrName).startswith ("Demand")):
            marginal_costs2.append(c.Pi)
    marginal_costs_df2 = marginal_costs2

    return Obj_value, v_w_df, v_pv_df, v_th_df, v_ens_df, i_w.X, i_pv.X, i_th.X, total_cost, w_cost, pv_cost, th_cost, ens_cost, marginal_costs_df, marginal_costs_df2, q_dd.X  # This line should be indented inside the function

    C_inv_W = 202.15
    C_inv_PV = 101.07
    C_inv_TH = 163.96
```

Investment viability

```
import pandas as pd
import matplotlib.pyplot as plt
import locale

locale.setlocale(locale.LC_ALL, 'es_ES.utf8')

w_ini = (QW_norm*i_w_df).T
w_final = (v_w_df).T
pv_ini = (QPV_norm*i_pv_df).T
pv_final = (v_pv_df).T
th_ini = (QTH_norm*Q_TH).T
th_final = (v_th_df).T

w_iv = w_final * marginal_costs_df
pv_iv = pv_final * marginal_costs_df
th_iv = th_final * marginal_costs_df
demand_iv = w_iv + pv_iv + th_iv

total_w_iv = w_iv.sum().sum()
total_pv_iv = pv_iv.sum().sum()
total_th_iv = th_iv.sum().sum()
total_demand_iv = demand_iv.sum().sum()

data = {
    'Market revenue': ['Wind', 'Solar', 'Thermal', 'Total'],
    'Cost [€]': [total_w_iv, total_pv_iv, total_th_iv, total_demand_iv]
}

iv_values_df = pd.DataFrame(data)

plt.figure(figsize=(12,6))
plt.plot(range(NT), w_iv, linewidth=1.0, label="Wind market revenue", color="blue")
plt.plot(range(NT), pv_iv, linewidth=2.0, label="Solar market revenue", color="gold")
plt.plot(range(NT), th_iv, linewidth=2.0, label="Thermal market revenue", color="red")
plt.plot(range(NT), demand_iv, linewidth=2.0, label="Total market revenue", color="black", linestyle = 'dotted')
plt.legend(loc='upper left')
plt.title("All market revenues")
plt.xlabel('Time [24h, resolution 5min]')
plt.ylabel('Cost [€]')
plt.grid(True)
plt.show()

styled_iv_values_df = iv_values_df.style.set_properties(
    **{'text-align': 'center','font-size': '120%','border': '1px solid black','padding': '10px'}
).set_table_styles(
    [dict(selector='th', props=[('text-align', 'center'), ('font-size', '130%'), ('border', '1px solid black'), ('padding', '10px')])]
).format({'Cost [€]': lambda x: locale.format_string('%1.2f €', x, True)})

display(styled_iv_values_df)
```

Long-term marginal costs

```
import matplotlib.pyplot as plt
import locale
import pandas as pd
from IPython.display import display

r = 0.065  # discount rate
n = 25     # lifetime of generators
investment_costs = {  # in €/MW
    'Wind': 900000,
    'Solar': 450000,
    'Thermal': 730000
}
operating_costs = {  # in €/MWh
    'Wind': 5,
    'Solar': 1.25,
    'Thermal': 45.02
}
capacity_factor = {  # in MWh
    'Wind': 0.5,
    'Solar': 0.25,
    'Thermal': 1
}

# Energy produced by each generator in MWh
energy_produced = {
    'Wind': 303060.39,
    'Solar': 285985.92,
    'Thermal': 220.421
}

total_energy_produced = sum(energy_produced.values())

energy_proportions = {generator: energy / total_energy_produced for generator, energy in energy_produced.items()}

annuity_factor = (r*(1+r)**n)/((1+r)**n - 1)

ltmc = {}
for generator in investment_costs.keys():
    annualized_investment_cost = investment_costs[generator] * annuity_factor
    ltmc_mw = annualized_investment_cost + operating_costs[generator] * 1000  # convert €/MWh to €/MW
    ltmc[generator] = ltmc_mw / (capacity_factor[generator] * 365)

total_ltmc = sum(ltmc[generator] * energy_proportions[generator] for generator in ltmc.keys())


colors = ['blue', 'gold', 'red', 'black']

plt.figure(figsize=(10, 6))
plt.bar(ltmc.keys(), ltmc.values(), color=colors)
plt.bar('Total', total_ltmc, color='black')

plt.title('Long-term Marginal Costs')
plt.xlabel('Energy Source')
plt.ylabel('LTMC [€ / MWh]')

plt.show()

locale.setlocale(locale.LC_ALL, 'es_ES.utf8')

df = pd.DataFrame.from_dict(ltmc, orient='index', columns=['LTMC'])
df.loc['Total'] = total_ltmc

styled_df = df.T.style.set_properties(
    **{'text-align': 'center','font-size': '120%','border': '1px solid black','padding': '10px'}
).set_table_styles(
    [dict(selector='th', props=[('text-align', 'center'), ('font-size', '130%'), ('border', '1px solid black'), ('padding', '10px')])]
).format(lambda x: locale.format_string('%1.2f € / MWh ', x, True)).hide(axis="index")

display(styled_df)
```