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UNIVERSIDAD PONTIFICIA
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MASTER'S DEGREE IN INDUSTRIAL ENGINEERING

MASTER'S FINAL THESIS

An investment model for renewable power resources in the context of a fully decarbonized system

Author: Jaime Masjuan Ginel

Director: Tomás Gómez San Román

Co-Director: Orlando Mauricio Valarezo Rivera

Madrid 2024

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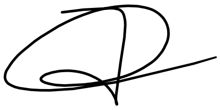

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MODELO DE INVERSIÓN PARA ENERGÍAS RENOVABLES EN EL CONTEXTO DE UN SISTEMA DECARBONIZADO

Autor: Jaime Masjuan Ginel

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Introducción. Este proyecto aborda la urgente necesidad global de reducir las emisiones de gases de efecto invernadero y avanzar hacia un sistema energético sostenible y descarbonizado. En este contexto, se desarrollaron dos modelos para optimizar la producción de energía renovable: uno anual de despacho económico y un modelo de inversión a largo plazo. Estos modelos incluyen el uso de instalaciones térmicas de respaldo y baterías de almacenamiento para maximizar la eficiencia energética. El enfoque principal es desarrollar un modelo de inversión robusto que tenga en cuenta las dinámicas financieras de las tecnologías renovables, cerrando así la brecha entre estas tecnologías y la estrategia financiera, y acelerando la transición hacia un sistema energético completamente descarbonizado.

El Proyecto. El objetivo principal de este proyecto es desarrollar un modelo de inversión adaptado al dinámico panorama de los recursos energéticos renovables en un sistema energético totalmente descarbonizado. Para ello, se busca mejorar la granularidad temporal del modelo de inversión, pasando de un marco diario a un análisis más detallado hora a hora, utilizando datos actualizados De Red Eléctrica Española (REE). Esta mejora permitirá una evaluación más precisa de los patrones de generación de energía renovable y su alineación con las fluctuaciones de la demanda.

El proyecto también incorpora tecnologías de respaldo y soluciones de almacenamiento de energía en el modelo de inversión, lo que permitirá evaluar de manera exhaustiva el papel de estos sistemas en asegurar un suministro de energía fiable, especialmente ante la intermitencia de las fuentes renovables. La implementación de estas tecnologías se hará en dos fases: primero las tecnologías de respaldo y luego el almacenamiento de energía.

Finalmente, el proyecto aborda la asignación óptima de inversiones entre diversas tecnologías renovables, evaluando los méritos económicos y técnicos de opciones como la solar, eólica y otras emergentes. El objetivo es determinar la mezcla óptima de tecnologías que maximice los beneficios del sistema energético. A través de un análisis riguroso y evaluaciones prospectivas, esta investigación pretende contribuir con un enfoque pragmático y visionario para guiar las decisiones de inversión en el sector de la energía renovable.

Modelo de Despacho Económico y Modelo de Inversión. Para este proyecto se han desarrollado dos modelos de optimización diferentes cuyo objetivo es el de reducir costes. Para ello, se han modelado las pertinentes restricciones con sus variables permitiendo así un correcto reparto de los recursos disponibles. En primer lugar, el Modelo de Despacho Económico consiste en el casamiento de la demanda con una oferta basada en energía solar, eólica, nuclear y térmica de respaldo. La idea de este modelo es tener una referencia que permita observar cómo se reparte la generación e identificar potenciales márgenes de mejora. En segundo lugar, el Modelo de Inversión, por otra parte, permite la posibilidad de incrementar la potencia instalada de cada una de las tecnologías a través de la inclusión de unos costes de inversión. En este modelo se van a poder añadir nuevos megavatios de energía solar y eólica, sumados a la inclusión de sistemas de almacenamiento de energía como el bombeo hidráulico y las baterías de litio.

Además, toda vez que se hayan ejecutado los modelos, se llevará a cabo un análisis económico basado en los costes marginales del sistema y utilizando la técnica del *uplift* económico. Para ello primero se obtendrán los beneficios por generador, utilizando los costes marginales como precio de mercado y los costes de producción. Con el beneficio total por generador a lo largo de un año obtenido, se elevará el precio de los generadores que tengan pérdidas en las horas en las que ellos marquen el precio marginal de mercado para poder conseguir que dichos generadores tengan viabilidad económica.

Resultados. Llevando a cabo un análisis de ambos modelos, se pueden obtener una serie de conclusiones sobre el funcionamiento del modelo.

Con respecto al Modelo de Despacho Económico, se han obtenido los siguientes resultados.

	Total Energy Dispatched (MWh)	Total Cost (€)	Cost per MWh (€/MWh)
Nuclear	61.016.277	1.403.374.371	23,00
Wind	58.223.834	582.238.342	10,00
Solar	31.091.866	155.459.333	5,00
Thermal	85.743.063	4.251.259.622	49,58
ENS	21.084	166.141.920	7.880,00
TOTAL	**236.096.125**	**6.558.473.588**	**27,78**

Table 1. Despacho total y coste por tecnología

Se observa de la tabla como la energía nuclear y la térmica son las mayores productoras de energía en este modelo a pesar de ser las más caras. Esto se debe principalmente a la falta de sistemas de almacenamiento que permitan reducir los vertidos que puedan tener las energías renovables y que abaraten los costes del sistema, y se debe también al margen para incluir aún más potencia instalada tanto en la energía solar como en la eólica.

Cabe destacar que la energía térmica, con un 36% de la energía producida para cubrir la demanda, acapara un 63% del coste de todo el sistema.

Finalmente, la energía no suministrada (ENS), a pesar de que no tiene un peso importante sobre el modelo, puede aparecer debido de nuevo a la falta de producción de energía por parte de las renovables en momentos concretos del año a causa de condiciones climatológicas y a la falta de sistemas de almacenamiento que ayuden durante esas horas a cubrir la demanda.

Para el Modelo de Inversión se pueden obtener también muchas conclusiones interesantes. Cabe destacar que se han aplicado previamente una serie de premisas que varían las condiciones iniciales: el precio de la energía térmica ha aumentado, la potencia instalada de energía nuclear se reduce en un 50% y aparecen los sistemas de almacenamiento. A continuación, se muestran las inversiones en cada tecnología.

Technology	Investment (MW)
Solar	33.483
Wind	21.018
Lithium Batteries	0
Hydro Pump	8.021

Table 2.Megavatios de inversión por tecnología en el Modelo de Inversión

Si bien la energía solar es la que más potencia instalada nueva recibe, esto es debido a que es la más barata. Las baterías de litio no reciben inversión bajo estas condiciones ya que tienen menos capacidad de almacenamiento que el bombeo hidráulico.

En la siguiente tabla se pueden apreciar los resultados del despacho.

	Total Energy Dispatched (MWh)	Total Cost (€)	Cost per MWh (€/MWh)
Nuclear	29.865.031,90	686.895.733,81	23,00
Wind	89.109.511,54	891.095.115,36	10,00
Solar	82.495.020,21	412.475.101,03	5,00
Thermal	39.506.665,80	1.943.993.142,03	49,21
Hydro Pump	14.636.971,07	43.910.913,22	3,00
Lithium Batteries	0,00	0,00	0,00
ENS	30,91	243.584,32	7.880,00
TOTAL	**255.613.231,44**	**6.717.452.276,81**	**26,28**

Table 3. Despacho total y coste por tecnología en el Modelo de Inversión

En este caso, se ve claramente como la energía renovable gana importancia gracias a los nuevos megavatios de potencia instalados para energía solar, eólica y de bombeo, logrando ser las energías dominantes en el modelo.

Al mismo tiempo, la energía no suministrada desaparece y el consumo de energía nuclear y térmica se desploma. El bombeo hidráulico, si bien es la tecnología más barata empleada en términos de costes de producción, tiene el coste extra de la amortización anual que requiere, junto con los nuevos megavatios de energía solar y térmica.

Para terminar de comprender si este modelo de inversión está ajustado, es decir, si es óptimo y por tanto no permite la inversión de nuevos megavatios si se quieren recuperar todos los costes, hay que comparar las anualidades de cada inversión con respecto a los beneficios obtenidos. Los beneficios serán calculados como ingresos a precio marginal menos costes fijos y variables. Así, los resultados obtenidos son los siguientes:

Technology	Profit per MW	Annuity
Solar	36.423 €	36.266 €
Wind	72.727 €	72.532 €
Hydro Pump	64.123 €	64.106 €

Table 4. Comparación de la anualidad con el beneficio generador por MW

Así, comparando estos parámetros, se ve como ambas cifras son muy parejas, si bien siempre es mayor el beneficio por megavatio instalado que la anualidad para poder cubrir este coste y no incurrir en pérdidas.

Como extra a este modelo de inversión, se han ejecutado diversas sensibilidades que permiten modificar las condiciones de partida del modelo de inversión para ver como cambiarían los resultados de este.

Conclusión. Para concluir, esta tesis buscó mejorar dos modelos para entender cómo puede evolucionar el mercado de energía con nuevas tecnologías renovables. Los objetivos fueron refinar el modelo previo, incorporar generadores térmicos de respaldo y sistemas de almacenamiento, y optimizar la inversión en tecnologías verdes. Se logró pasar a un modelo horario, utilizar múltiples generadores térmicos y añadir sistemas de almacenamiento, haciendo el sistema más confiable y ecológico. También se demostró cómo se realiza la asignación óptima de inversiones comparando costes y beneficios.

Al comparar el Modelo de Despacho Económico y el Modelo de Inversión, se concluye que, sin inversión, la energía renovable usada es del 40%, lejos de los objetivos para 2030. Reducir la energía nuclear y aumentar la solar y eólica no afecta la fiabilidad del sistema. Los sistemas de almacenamiento son clave para la estabilidad y reducción de costos. Esta herramienta ayuda a determinar el número óptimo de megavatios a desarrollar para evitar pérdidas económicas y asegurar la estabilidad del sistema. En resumen, los modelos identificaron un equilibrio entre necesidades operativas a corto plazo y objetivos a largo plazo, resultando en un sistema energético más confiable, sostenible y rentable.

AN INVESTMENT MODEL FOR RENEWABLE POWER RESOURCES IN THE CONTEXT OF A FULLY DECARBONIZED SYSTEM

Autor: Jaime Masjuan Ginel

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Co-Director: Orlando Mauricio Valarezo Rivera

Introduction. This project addresses the urgent global need to reduce greenhouse gas emissions and move towards a sustainable and decarbonized energy system. In this context, three models were developed to optimize renewable energy production: a daily model, an annual economic dispatch model, and a long-term investment model. The project phases include the use of backup thermal installations and storage batteries to maximize energy efficiency. The primary focus is to develop a robust investment model that considers the financial dynamics of renewable technologies, bridging the gap between these technologies and financial strategy, thereby accelerating the transition to a fully decarbonized energy system.

The Project. The main goal of this project is to develop an investment model tailored to the dynamic landscape of renewable energy resources within a fully decarbonized energy system. To achieve this, the project aims to improve the temporal granularity of the investment model, shifting from a daily framework to a more detailed hour-by-hour analysis using up-to-date data from Red Eléctrica Española (REE). This improvement will enable a more precise assessment of renewable energy generation patterns and their alignment with demand fluctuations.

The project also incorporates backup technologies and energy storage solutions into the investment model, allowing for a comprehensive evaluation of the role these systems play in ensuring a reliable energy supply, especially given the intermittency of renewable sources. The implementation of these technologies will occur in two phases: first, the backup technologies, and second, energy storage solutions.

Finally, the project addresses the optimal allocation of investments among various renewable technologies, evaluating the economic and technical merits of options such as solar, wind, and other emerging technologies. The objective is to determine the optimal mix of technologies that maximizes the benefits of the energy system. Through rigorous analysis and forward-looking assessments, this research aims to provide a pragmatic and visionary approach to guide investment decisions in the renewable energy sector.

Economic Dispatch Model and Investment Model. Two different models have been developed for this project through an optimization model aimed at reducing costs. The relevant constraints and variables were modeled to ensure the proper allocation of available resources. The Economic Dispatch Model involves matching demand with a supply based on solar, wind, nuclear, and backup thermal energy. The idea of this model is to provide a reference that allows observing how generation is distributed and identifying potential areas for improvement. The Investment Model, on the other hand, allows for the possibility of increasing the installed capacity of each technology through the inclusion of investment costs. In this model, new megawatts of solar and wind energy can be added, along with the inclusion of energy storage systems such as hydraulic pumping and lithium batteries.

Additionally, once the models are executed, an economic analysis will be conducted based on the system's marginal costs using the economic uplift technique. First, the benefits per generator will be obtained using marginal costs as the market price and production costs. With the total annual benefit per generator, the price of generators that incur losses during the hours they set the marginal market price will be raised to ensure their economic viability.

Results. Conducting an analysis of both models allows us to draw several conclusions regarding their operation.

Regarding the Economic Dispatch Model, the following results were obtained.

	Total Energy Dispatched (MWh)	Total Cost (€)	Cost per MWh (€/MWh)
Nuclear	61.016.277	1.403.374.371	23,00
Wind	58.223.834	582.238.342	10,00
Solar	31.091.866	155.459.333	5,00
Thermal	85.743.063	4.251.259.622	49,58
ENS	21.084	166.141.920	7.880,00
TOTAL	**236.096.125**	**6.558.473.588**	**27,78**

Table 5. Total Dispatch and Cost per Technology

The table shows that nuclear and thermal energy are the largest producers in this model despite being the most expensive. This is primarily due to the lack of storage systems that could reduce the curtailment of renewable energies and lower system costs. Additionally, there is still room to add more installed capacity in both solar and wind energy.

It is noteworthy that thermal energy, providing 36% of the energy to meet demand, accounts for 63% of the total system cost. Lastly, the occurrence of Energy not Supplied (ENS), though not significant in this model, may appear due to intermittent renewable energy production during specific periods of the year, influenced by weather conditions and the absence of storage systems to cover demand during those hours.

For the Investment Model, several interesting conclusions can also be drawn. It is important to highlight that initial conditions were modified: the price of thermal energy increased, nuclear energy capacity was reduced by 50%, and storage systems were introduced. The investments in each technology are shown below.

Technology	Investment (MW)
Solar	33.483
Wind	21.018
Lithium Batteries	0
Hydro Pump	8.021

Table 6.Investment MW per Technology

Solar energy receives the highest new installed capacity investment because it is the least expensive. Under these conditions, lithium batteries do not receive investment as they have lower storage capacity compared to hydraulic pumping.

The results of the dispatch are displayed in the following table.

	Total Energy Dispatched (MWh)	Total Cost (€)	Cost per MWh (€/MWh)
Nuclear	29.865.031,90	686.895.733,81	23,00
Wind	89.109.511,54	891.095.115,36	10,00
Solar	82.495.020,21	412.475.101,03	5,00
Thermal	39.506.665,80	1.943.993.142,03	49,21
Hydro Pump	14.636.971,07	43.910.913,22	3,00
Lithium Batteries	0,00	0,00	0,00
ENS	30,91	243.584,32	7.880,00
TOTAL	**255.613.231,44**	**6.717.452.276,81**	**26,28**

Table 7. Total Dispatch and Cost per Technology for the IM

In this case, it is evident that renewable energy gains importance with the addition of new megawatts of installed capacity for solar, wind, and pumped hydro, becoming dominant energy sources in the model. Simultaneously, Unsupplied Energy disappears, and the consumption of nuclear and thermal energy declines. Despite hydraulic pumping being the least expensive technology in terms of production costs, it incurs additional annual amortization costs, alongside the new megawatts of solar and thermal energy.

To conclude whether this investment model is well-adjusted, that is, if it is optimal and therefore does not allow for the investment of new megawatts unless all costs are recovered, the annuities of each investment need to be compared with the benefits obtained. Benefits will be calculated as marginal price revenues minus fixed and variable costs. Thus, the results obtained are as follows:

Technology	Profit per MW	Annuity
Solar	36.423 €	36.266 €
Wind	72.727 €	72.532 €
Hydro Pump	64.123 €	64.106 €

Table 8. Comparison between Annuity and Profit per MW

Thus, comparing these parameters, it is evident that both figures are quite close, although the profit per installed megawatt is always greater than the annuity to cover this cost and avoid losses. As an additional aspect to this investment model, various sensitivities have been applied to modify the initial conditions of the investment model to see how its results would change.

Conclusion. In conclusion, this thesis aimed to enhance two models to understand how the energy market can evolve with new renewable technologies. The objectives were to refine the existing model, incorporate backup thermal generators and storage systems, and optimize investments in green technologies. The project successfully transitioned to an hourly model, utilized multiple thermal generators, and introduced storage systems, enhancing system reliability and environmental friendliness. It also demonstrated the optimal allocation of investments by comparing costs and benefits.

Comparing the Economic Dispatch Model and the Investment Model, it is concluded that without investment, renewable energy usage stands at 40%, falling short of the 2030 targets.

Reducing nuclear energy while increasing solar and wind has no impact on system reliability. Storage systems are crucial for stability and cost reduction. This tool helps determine the optimal number of megawatts to develop to avoid economic losses and ensure system stability. In summary, the models identified a balance between short-term operational needs and long-term objectives, resulting in a more reliable, sustainable, and cost-effective energy system.

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1. INTRODUCTION

The global imperative to address climate change and transition towards a sustainable, decarbonized energy system stands as one of the most pressing challenges of our time. The urgency to reduce greenhouse gas emissions, mitigate environmental degradation, and secure a resilient energy future has propelled renewable power resources to the forefront of this journey. As nations and industries worldwide commit to ambitious decarbonization targets, the strategic allocation of financial resources becomes one of the biggest challenges for accelerating the transition towards a fully decarbonized energy landscape.

The transition towards renewable power sources is not merely a technological shift, but a systemic transformation that necessitates a harmonious integration of economic, environmental, and technological considerations. Achieving a fully decarbonized energy system entails not only the proliferation of renewable technologies but also an astute understanding of their financial dynamics. In this context, the development of a robust investment model tailored explicitly to the intricacies of renewable power resources represents a critical step forward.

This project embarks on a comprehensive exploration of this imperative, seeking to bridge the gap between renewable energy technologies and financial strategy. This is the third part of a series of theses that have already addressed this issue. The first one consisted of the comparison of long-term versus short-term marginal costs that characterize a 100% renewable market [1]. The second one, developed the simulation tools that are going to be used in this project, providing this thesis with a first approach to the problem [2].

The second thesis also provides the results of a first 100% renewable power market simulation based on solar, wind, and thermal power. In this project, the aim will be to introduce new technologies in two phases. The first phase will include the use of backup thermal installations that will provide energy to the system whenever it is needed, and the second phase will add storage batteries so that all the energy that can be produced but exceeds the demand can be stored to be exploited when the production costs are higher.

The idea behind the algorithm that will feed our system is the one that helps today's electricity market with non-renewable energy. As electricity is a commodity, the differentiation between different producers is non-existent, which means that when a supplier wants to enter the market, it needs to minimize its production and operating costs so that its business will be profitable. Thus, the company that produces energy with lower costs will obtain the bigger profits. For this system, the generation source stops producing once it reaches its capacity, or all the demand is met.

Once the system is developed, the investment model will be created. The investment model for renewable technologies involves assessing upfront costs, potential revenues, and their impact on electricity prices. By evaluating factors like installation, maintenance, and energy production, investors can estimate returns. Additionally, adding a unit of renewable tech affects market dynamics, potentially lowering prices due to increased supply and competition; a study will be conducted to see how this could affect the system.

1.1.Motivation

In a world that is constantly evolving, the imperative for a sustainable and decarbonized energy system stands as one of the biggest challenges that humanity will face in the next decade. As countries are commencing to invest large amounts of money in renewable energy, pursuing the goal of a fully decarbonized system, this project appeared as an opportunity to combine the engineering and business skills.

As this thesis is born with the clear vision of developing a bridge between the gap between renewable energy technologies and financial strategy, this research strives to contribute a forward-thinking approach to guide investment decisions. Through rigorous analysis, empirical case studies, and forward-looking scenario assessments, this project aims to illuminate pathways toward a resilient, low-carbon energy system.

This project adds several complexities to the previous model that will allow it to be more realistic. These complexities will be the inclusion of start-up and shut-down costs regarding the use of backup thermal generators, one nuclear generator, and storage systems in the shape of lithium batteries and hydro pump storage.

1.2. Project's Objectives

The primary goal of this project is to advance the development of an investment model that suits the dynamic landscape of renewable power resources within the framework of a fully decarbonized energy system. Building upon an existing foundation, the project sets out to achieve several main objectives:

- Refinement of Temporal Granularity: The project aims to enhance the temporal granularity of the previous investment model [1], transitioning from a day-to-day framework to a more granular hour-to-hour analysis. This finer resolution will enable a more precise assessment of renewable energy generation patterns and their alignment with demand fluctuations. Also, it will be combined with the use of up-to-date data that will be obtained from the Spanish System Operator (REE).
- Incorporation of Backup Technologies and Energy Storage: Recognizing the importance of grid reliability, the project will incorporate backup technologies and energy storage solutions into the dispatch and investment models. This addition will allow for a comprehensive evaluation of energy storage and backup systems' role in ensuring a reliable energy supply, particularly in the context of intermittent renewable sources. The main idea for this objective is to include these new additions to the model in two phases, first, the Backup Technologies and second, the Energy Storage.
- Optimal Allocation of Investments Across Renewable Technologies: The project addresses the critical decision of allocating investments among various renewable technologies. This involves evaluating the economic and technical merits of options such as solar, wind, and other emerging renewable sources such as storage. The objective is to determine the optimal mix of technologies that maximizes the overall benefits of the energy system.

By pursuing these objectives, the project plans to deliver an investment model that optimizes financial returns and advances the transition towards a sustainable, decarbonized energy future. Through rigorous analysis and forward-looking scenario assessments, this research aims to contribute a pragmatic and forward-thinking approach to guide investment decisions in the renewable energy sector.

1.3.Structure

This document will be divided into four main sections: the State of the Art, the Methodology, the Results of the model, and the Conclusion.

The State of the Art will consist in making a brief presentation of the Thesis topic, explaining how the energy markets work, the dispatch models, the investment models in the energy markets context, and the explanations of the previous Thesis, which are the starting point of this project. Moving into the Methodology, the dispatch and investment models will follow a similar structure: the technologies used will be explained, the system's costs and demand will be shown, and finally, the formulation of the optimization problem will be presented.

The results of the project will be shown in the final two sections. First, the economic and dispatch analysis will be discussed, as well as how these results fit within the project's objectives. Second, for the investment model, there will be a baseline case, which will be the starting point prior to several modifications. Thus, several sensitivities may give different results for different future scenarios that could occur. Finally, in the Conclusion section the summary of the project will be made, understanding the main and most important results from the Thesis.

2. State of the Art

The state of the art in energy systems encompasses several key areas, including economic dispatch methodologies, investment models, energy market dynamics, and marginal cost analysis. Understanding these facets is pivotal for strategic decision-making within the energy sector. This section provides a comprehensive overview of modern trends in these areas, drawing from recent research and industry practices.

2.1. Economic Dispatch Methodologies

Economic dispatch methodologies are essential for optimizing power generation within an electrical grid. Their primary objective is to minimize total production costs while meeting electricity demand and adhering to operational constraints. These methodologies have evolved to accommodate changes in power system structure, technological advancements, and environmental considerations [3].

Traditionally formulated as optimization problems, economic dispatch aims to minimize the sum of generation costs subject to various constraints like transmission and generator operational limits. Techniques such as linear programming, dynamic programming, and metaheuristic algorithms like genetic algorithms are commonly used to solve these problems. It is closely related to the unit commitment problem, which determines the optimal power generation schedule for a set of plants over a specified time horizon. This involves considering start-up and shut-down costs, minimum up and down times, and other operational constraints alongside generation costs, such as those in this model.

In electricity markets, economic dispatch forms the basis of market clearing mechanisms that match supply with demand. Market operators utilize economic dispatch algorithms to determine clearing prices and quantities of electricity across different time periods and market participants. The integration of renewable energy sources, which are variable and uncertain, poses challenges for economic dispatch. Advanced methodologies incorporate forecasting techniques and stochastic optimization approaches to manage the integration of renewables while maintaining system reliability and minimizing costs.

Economic dispatch methodologies are critical for efficient power system operation, allowing utilities and grid operators to balance supply and demand effectively while optimizing resource utilization. Continuous research and development in this field are vital to address emerging challenges and opportunities in the evolving energy landscape.

2.2. Investment Models

Investment models are foundational frameworks within energy systems, essential for assessing the financial viability and risk associated with energy projects or technologies. They serve to guide decision-making processes regarding resource allocation and project prioritization. These models typically integrate components such as capital costs, operating expenses, revenue streams, and financing options. Moreover, they consider the characteristics and performance of different energy technologies, ranging from renewable sources like solar and wind to conventional power generation such as coal and natural gas power plants [4].

A significant aspect of investment models is their incorporation of risk analysis techniques to quantify and manage uncertainties associated with energy projects. These techniques may include sensitivity analysis, scenario-based analysis, or probabilistic risk assessment, allowing stakeholders to evaluate the impact of uncertain factors on project economics and financial outcomes. For this project, the analysis will be made only based on economic parameters, thus leaving out the complexities that may come from different risks that could affect the model.

Furthermore, investment models serve as decision-support tools by providing stakeholders with insights into the financial implications of different investment scenarios and policy options. By facilitating the comparison of alternative projects or investment strategies based on criteria like net present value, internal rate of return, and payback period, these models empower decision-makers to make informed choices.

Additionally, investment models play a vital role in evaluating the effectiveness of energy policies, incentives, and regulations. By assessing their impact on project economics and market dynamics, policymakers can design more effective policies to promote investment in sustainable energy infrastructure and accelerate the transition to a low-carbon energy system.

2.3. Energy Market Dynamics

Energy market dynamics encompass the complex interplay of various factors shaping the operation and evolution of energy markets. These dynamics are influenced by a combination of regulatory policies, technological advancements, consumer behavior, and environmental considerations.

One significant trend in energy market dynamics is the increasing penetration of renewable energy sources. The declining costs of technologies such as solar and wind power, coupled with supportive policies and incentives, have rapidly expanded renewable energy capacity worldwide. This shift towards renewables has profound implications for market structures, pricing mechanisms, and grid operations, as intermittent and variable energy sources require new approaches to grid management and market design. One of the ideas of this project is to show the relevance and importance that these new technologies are gaining in the market, combining this with the storage systems that can help to reduce the curtailments produced at certain times by solar and wind power.

Another emerging trend is the decentralization of energy systems, driven by advancements in distributed generation, energy storage, and demand-side management technologies. Distributed energy resources, including rooftop solar panels, battery storage systems, and electric vehicles, empower consumers to play a more active role in energy production, consumption, and trading. This trend toward decentralization is reshaping traditional utility business models and challenging centralized approaches to energy planning and regulation [5].

Additionally, integrating smart grid technologies is transforming how energy is generated, transmitted, and consumed. Smart meters, sensors, and advanced analytics enable real-time monitoring and control of grid operations, facilitating greater grid reliability, efficiency, and resilience. Moreover, demand response programs and dynamic pricing mechanisms leverage smart grid capabilities to incentivize demand-side flexibility and optimize resource utilization in response to fluctuating supply and demand conditions.

2.4. Marginal Costs Analysis

Marginal cost analysis is a fundamental economic concept and plays a crucial role in various sectors, including energy. It involves quantifying the incremental cost of producing an additional unit of a good or service. In the context of the energy sector, marginal cost analysis is particularly relevant for determining the cost of producing electricity. It considers the additional costs incurred by producing one more unit of electricity, taking into account factors such as fuel costs, variable operating expenses, and any other expenses directly attributable to increasing production. It helps utilities and grid operators make efficient production decisions by comparing the marginal cost of generating electricity with the prevailing market price. [6]

One key application of marginal cost analysis is economic dispatch, where generators are dispatched in merit order of increasing marginal cost to meet electricity demand at the lowest possible cost. By prioritizing low-cost generators and minimizing the use of high-cost generators, economic dispatch helps optimize resource utilization and minimize production costs while maintaining system reliability. Marginal cost analysis also informs pricing mechanisms in electricity markets, where generators are compensated based on their marginal cost of production. In competitive wholesale markets, generators offer electricity at prices equal to their marginal cost, ensuring efficient resource allocation and preventing market power abuse under competition.

Moreover, marginal cost analysis is instrumental in evaluating the economic impacts of various policy interventions, such as carbon pricing mechanisms or renewable energy subsidies. By quantifying the marginal costs associated with different energy technologies and production methods, policymakers can assess the cost-effectiveness of policy measures and design more efficient and equitable energy policies.

Overall, marginal cost analysis provides valuable insights into the cost structure of electricity production and helps inform decision-making processes in the energy sector, contributing to efficient resource allocation and achieving economic and environmental objectives.

3. Methodology

3.1. Introduction

The Economic Dispatch Model is an essential tool in the operation of power systems. Its purpose is to identify the most cost-efficient method of power generation to meet the required demand, factoring in operational costs and system constraints. The model primarily aims to minimize overall operational expenses, relying primarily on renewable energy sources and nuclear power. Fuel-based power generation is utilized when those sources are insufficient to meet the demand. The model aims to prevent power shortages, referred to as 'energy not supplied' (ENS) since the costs associated with ENS are significantly higher than those of any other form of energy production. This optimization is typically performed on a daily basis. Excess production can lead to curtailments, where surplus energy is wasted or stored, representing a substantial opportunity cost. The model must also adhere to technical restrictions, such as maintaining power balance and observing generation limits. The Economic Dispatch Model is vital for ensuring the economic efficiency of power system operations.

This chapter will be divided into five different sections. The first one will define the model's input such as the demand or the generation techniques used. The second, is going to explain the costs used in the different models. Next, the economic dispatch model will be explained as a pure assignation of the existing resources to match the demand. The fourth section will describe the investment model to optimally expand the existing system. Finally, the economic part of the project will be introduced by explaining how the marginal costs, and uplifts are going to be used to obtain the profitability of each generator.

3.2. Model Inputs

3.2.1. Demand

Demand refers to the maximum amount of electrical power consumed at a given time, as opposed to energy, which is the amount of power consumed over a period [7]. Electricity demand is a critical aspect of power system operations, influencing electrical power generation, transmission, and distribution. Understanding the factors that drive demand and the patterns in which it fluctuates is essential for maintaining system reliability, optimizing operational efficiency, and planning future infrastructure investments. This demand can be categorized into different types, including baseload, which represents the continuous minimum demand, and peak load, which represents the highest demand.

Several factors influence electrical demand, including economic activities, weather conditions, and technological advancements. Economic factors, such as industrial production and commercial activities, can significantly impact electricity consumption. Weather and seasonal variations also play a major role, with higher demand in summer and winter due to heating and cooling needs. Social and demographic factors, including population growth and urbanization, contribute to changing demand patterns. Additionally, technological advancements, such as the adoption of energy-efficient appliances and the increase in electric vehicle usage, shape the future of electrical demand.

As these factors affect the electrical demand, it exhibits fluctuations on various timescales. Daily fluctuations are driven by human activities, with peaks typically occurring in the morning and evening. Weekly fluctuations reflect differences between weekdays and weekends, while seasonal fluctuations are influenced by climate and weather conditions. Long-term trends in demand can be affected by factors such as economic development, population growth, and advancements in energy efficiency.

Now that the concept of electrical demand has been defined, it seems natural to talk about the demand data used in this project. The data of the demand of 2022 composed of 8760 hours from REE has been considered so that this model can be adjusted to reality as much as possible. Figure 1 presents the demand used for the yearly model (8760h).

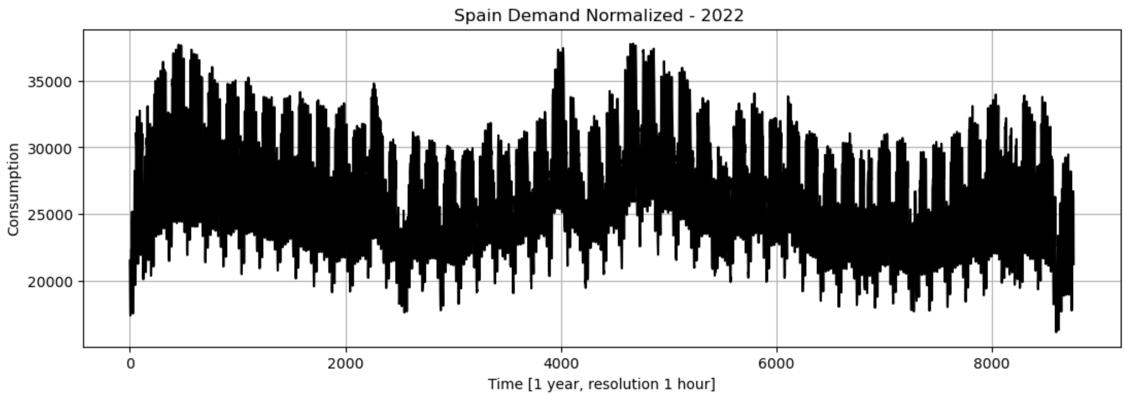

Figure 1. Spanish demand for 8760h in 2022

As it has been mentioned, fluctuations can be seen throughout the whole year depending on the human activity and the weather mainly (during the night there is less demand and during the summer and winter months the demand increases due to more extreme temperatures).

3.2.2. Generation Technologies

For this project, there have been several technologies modeled; these technologies are solar photovoltaic, wind, nuclear, backup thermal, hydro pump, and lithium batteries. The last two will only be modelled in the investment model to see how the original model could be improved while trying to achieve its goal. Some of the technologies that can be found in this project are not renewable (nuclear and back-up thermal) so one of the objectives for the investment model will be to reduce the amount of demand covered by these technologies.

Solar Energy

Starting with solar energy, in Spain, it has seen significant growth and development over the past few decades. Spain has been a pioneer in the deployment of solar energy, particularly solar photovoltaic (PV) and solar thermal technologies. The country's favorable climate, with high levels of sunlight, makes it an ideal location for solar energy generation. Spain is one of the leading countries in Europe in terms of solar PV installations. The Spanish government has implemented various policies and incentives to promote the adoption of solar PV, such as feed-in tariffs and renewable energy auctions. As a result, the installed capacity of solar PV has grown substantially.

Figure 2. Solar PV plant in Spain

By the end of 2023, Spain had an installed solar PV capacity of approximately 20 GW [8], positioning it among the top countries globally for solar power generation. Based on this value and the data provided by REE [9], it has been possible to create the generation curve of the amount of solar PV energy generated in Spain in 2022, as shown in Figure 3.

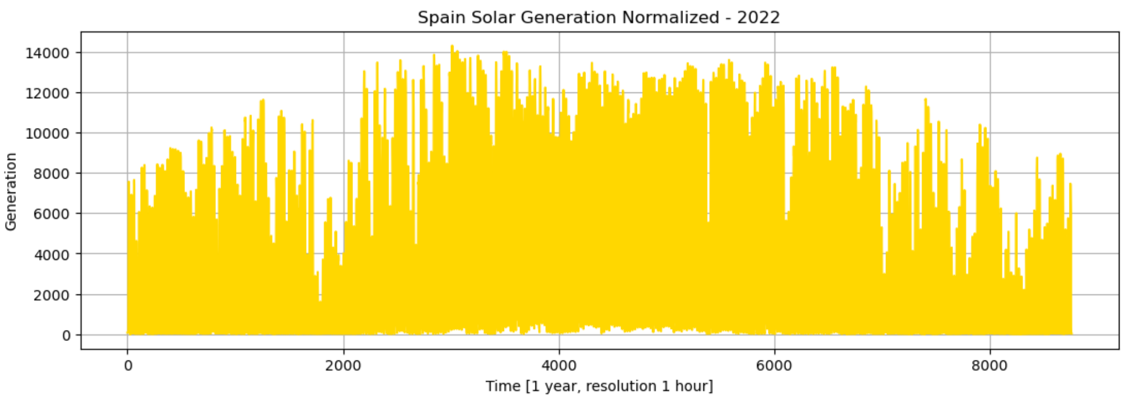

Figure 3. Spain's Solar Generation in 2022

Wind Energy

The next generation technology is wind power; in Spain, it has experienced significant growth and development over the past few decades. Spain is a global leader in wind energy, thanks to its favorable geographic conditions and strong government support. The country has a diverse range of wind resources, particularly in regions such as Galicia, Castilla y León, and Andalusia, which have high wind speeds and are ideal for wind power generation. The Spanish government has implemented various policies and incentives to promote the adoption of wind power. These include feed-in tariffs, renewable energy auctions, and subsidies, encouraging investment in wind energy projects. As a result, Spain has become one of the top countries in the world in terms of installed wind power capacity. By the end of 2023, Spain had an installed wind power capacity of approximately 30 GW [10], making it one of the largest producers of wind energy globally. Spain's wind power sector comprises both onshore and offshore wind farms. Onshore wind farms are more common and widespread, while offshore wind farms, although less developed, are gaining attention due to technological advancements and the potential for higher energy yields.

Figure 4. Wind power plant in Spain

The growth of wind power in Spain has had substantial economic and environmental benefits. Economically, the wind energy sector has created numerous jobs, attracted significant investment, and reduced the country's reliance on imported fossil fuels. Environmentally, wind power has contributed to reducing greenhouse gas emissions and helped Spain move closer to its renewable energy targets and climate goals.

As has been mentioned, by the end of 2022, Spain had an installed wind capacity of approximately 30 GW [10], positioning it among the top countries globally for wind power generation. Based on this value and the data provided by REE [9], it has been possible to create the generation curve of the amount of wind generated in Spain in 2022, as it is shown in Figure 5.

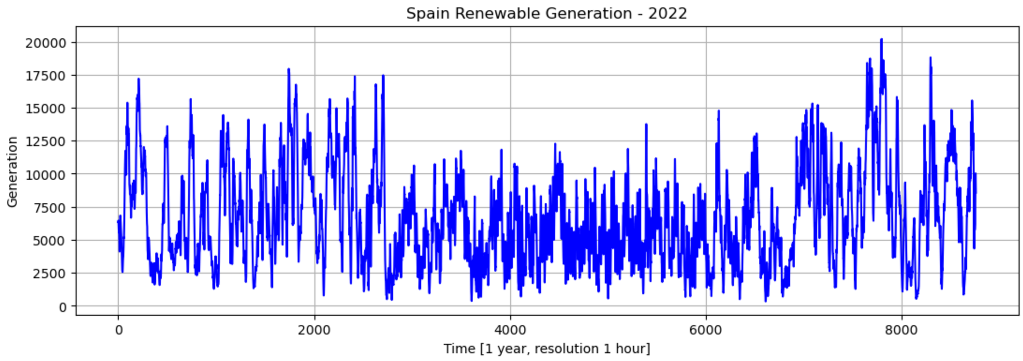

Figure 5. Spain's Wind Power Generation

Nuclear Energy

The third technology that will be part of this model is nuclear technology. Nuclear power in Spain has played a significant role in the country's energy mix for several decades. Spain's nuclear energy sector has been a key component of its strategy to ensure a stable and reliable electricity supply, while also contributing to the reduction of greenhouse gas emissions. The country operates several nuclear power plants, consistently providing a substantial portion of its electricity.

Spain's nuclear power industry began in the mid-20th century, and today, it includes seven operational nuclear reactors spread across five plants: Almaraz, Ascó, Cofrentes, Vandellós, and Trillo. These plants are strategically located to supply electricity to various regions of the country. As of 2023, nuclear power accounts for around 20% of Spain's total electricity generation, making it a crucial part of the energy landscape.

Nuclear power in Spain offers several advantages, including a stable and continuous power supply, which is not subject to the intermittency issues that affect renewable energy sources like wind and solar. This reliability makes nuclear power essential to Spain's baseload electricity generation. Additionally, nuclear power plants have a relatively low operating cost once constructed, providing an economical source of electricity over the long term.

However, the nuclear power sector in Spain faces several challenges. These include concerns about nuclear safety, the management of radioactive waste, and the high costs associated with constructing and decommissioning nuclear plants. Public opinion on nuclear power is mixed, with some segments of the population advocating for a reduction in nuclear energy use in favor of renewable sources.

Taking all these factors into account, it has been modeled in the project one generator of 7 GW [11] of nuclear power that will always operate between 90% and 100% of capacity non-stop throughout the whole year. This matches the reality as nuclear power plants tend to operate for long periods of time without stopping. For the investment model, one of the ideas will be to reduce its capacity to 50% or even take nuclear energy out of the model to see how the system will respond.

Figure 6. Nuclear Power Plant in Spain

Back-up Thermal Energy

Another technology that will be used is the backup thermal power. It plays a vital role in ensuring the stability and reliability of the country's electricity supply. Thermal power plants, which primarily use fossil fuels such as natural gas, coal, and oil, are a critical component of the energy mix, especially as backup sources that can quickly respond to fluctuations in electricity demand and supply. These plants are essential for providing a stable power supply when renewable energy sources like wind and solar are intermittent.

The thermal power sector includes a variety of plants, ranging from combined cycle gas turbine (CCGT) plants to coal-fired and oil-fired power stations. Combined cycle plants, which use gas and steam turbines to generate electricity, are particularly valued for their efficiency and flexibility. These plants can be ramped up or down relatively quickly, making them ideal for balancing the grid during periods of high demand or low renewable output.

Thermal power plants offer several advantages, including their ability to provide a continuous and controllable power supply, which is crucial for maintaining grid stability. Unlike renewable sources that depend on wind or sunlight, these plants can operate independently of weather conditions. This makes them essential for meeting peak demand periods and ensuring a reliable power supply when renewable generation is insufficient.

For this project, the backup thermal energy has been modeled as 25 generators with a capacity of 1 GW each. The idea of these generators is that each one of them has a different price, with generator number 1 being the cheapest and generator number 25 the most expensive. The differences between the cost production of one generator to another will be of 1 €/MWh. This supply will be in charge of covering the peaks of the curve that cannot be matched by the sum of the renewable energies and the nuclear power plant.

Storage Systems – Hydro Pump and Lithium Batteries

Finally, the last technology that will be used will be storage in the form of lithium batteries and hydro pumps. Energy storage technologies are crucial to Spain's energy transition towards a more sustainable and resilient power system. These storage solutions are vital in balancing supply and demand, integrating intermittent renewable energy sources, and ensuring grid stability.

On one hand, lithium-ion batteries have emerged as a leading energy storage technology, offering high energy density, rapid response times, and scalability. In Spain, lithium-ion batteries are deployed in various applications, including grid-scale energy storage, backup power for critical infrastructure, and integration with renewable energy projects. On the other hand, pumped hydro storage is one of the oldest and most widely deployed forms of energy storage, providing grid stability and flexibility for decades. In Spain, pumped hydro storage facilities are located in mountainous regions, where excess electricity is used to pump water from lower reservoirs to higher ones during periods of low demand. When electricity demand is high, water is released from the higher reservoirs, passing through turbines to generate electricity.

For this project, the storage has been modeled as an investment variable so that it is the model the one who decides in which technology and how much does modeled as an investment variable so that it is the model the one who decides which technology and how much it wants to invest. The lithium-ion batteries and the hydro pump will have their own investment, fixed, and operating costs.

3.3. Costs parameters used in the models

The main idea of this section is to describe and explain the different costs that will be used to model both the Economic Dispatch and the Investment Model. This cost will be the parameter that determines which technology will be first assigned to the supply the demand to achieve the minimum operational cost. Also, for the Investment Model, several new costs will appear as part of the cost and strategy of the new investment that will appear in the generation technologies.

3.3.1. Operating and Maintenance Costs

Operating and maintenance (O&M) costs are crucial for power plants' efficient and reliable operation. These costs are divided into fixed and variable categories. Fixed costs include labor, administrative expenses, long-term maintenance contracts, and infrastructure upkeep, while variable costs encompass fuel, consumables, wear and tear, and short-term maintenance. Different power generation types have specific O&M costs: wind power has low fixed costs but higher repair costs, solar PV has minimal variable costs, thermal power has high fuel and maintenance costs, and nuclear power has significant fixed costs due to safety and regulatory requirements.

In this case, for solar and wind power, it has only been modeled one O&M cost at the values of 5€/MWh and 10€/MWh, respectively. The idea is to have a simple model that, in this case, represents the advantages of using this type of energy to cover the demand as these costs are lower than other technologies. For the backup, thermal costs have been modelled from 35€/MWh to 60€/MWh, increasing the cost by 1€/MWh as a new thermal generator is dispatched. The idea is to have this technology used only when the other technologies cannot cover all the demands that the system needs. Moreover, this technology will have a start-up and shut-down costs of 20.000€ every time a generator starts or stops, giving the model a bigger parallelism with reality. Finally, the nuclear cost is also a variable cost defined as 23€/MWh for both models and will cover all the O&M costs of this type of power. All these costs have been defined and assumed for both models.

For the Storage systems, the costs have been assumed and divided into variable and fixed costs to understand better how these systems operate. For the hydro pump, the O&M fixed cost will be 12.000€/MW per year and the O&M variable cost will be 3€/MWh. On the other hand, for the lithium batteries, the O&M fixed cost will be 5500€/MW per year, and the O&M variable cost will be 0,00025€/MWh.

Table 9 summarizes all the O&M costs per technology considered in this thesis:

Technology	Variable Cost (€/MWh)	Fixed Cost (€/MW)	Start-up / Shut-down Cost (€)
Solar	5	-	-
Wind	10	-	-
Nuclear	23	-	-
Back-up Thermal	35 - 60	-	20.000
Hydro Pump	3	12.000	-
Lithium Batteries	0,00025	5.500	-

Table 9. Breakdown of O&M costs per technology

3.3.2. Investment Costs

Investment costs are crucial for expanding power generation facilities, divided into initial and ongoing capital expenditures. Initial costs cover construction, equipment purchase, installation, and permitting, while ongoing investments include upgrades, capacity expansions, and Research and Development (R&D). For example, wind power has high initial costs for turbines and site preparation, with moderate ongoing investments for upgrades. Solar PV also has significant initial costs for panels and installation but lower ongoing expenses. Thermal and nuclear power plants face high initial and ongoing costs due to their complexity and safety requirements. Effective management of these costs is essential for power generation projects' economic feasibility and sustainability, ensuring a stable and reliable energy supply.

For this model, the investment will only be made in renewable energy technologies such as wind, solar and batteries. For that, there will be an investment cost per year that will be obtained with the CAPEX, the lifespan and the interest rate.

For solar and wind technologies, the lifespan has been estimated at 30 years, and the interest rate is 7%. The CAPEX per MW of installed technology will be 900.000€ for wind power and 450.000€ for solar power [1]. All these values give the model an annuity of 72.532€/MW for wind power and 36.266€/MW for solar power.

For the storage systems, hydro pump, and lithium batteries, the interest rate will be 7% as well, but the lifespan will be 60 years for hydro pump and 10 years for lithium batteries. The CAPEX for hydro pump will be 900.000 €/MW and 632.122 €/MW for lithium batteries. Taking all into account, the annuities for the Investment Model are going to be 64.106 €/MW for hydro pump and 90.000 €/MW for lithium batteries [12].

Table 10 presents all the parameters for the investment costs per technology:

Technology	Lifespan (years)	Rate (%)	CAPEX (€/MW)	Annuity (€/MW per year)
Solar	30	7%	450.000	36.266
Wind	30	7%	900.000	72.532
Hydro Pump	60	7%	900.000	64.106
Lithium Batteries	10	7%	632.122	90.000

Table 10. Investment parameters for every technology

3.4.Economic Dispatch Model

This subsection will dive into the Economic Dispatch Model, which is the base case of this project. The idea is to match the electricity demand with the power supplied by the different generator types previously mentioned. For this Model, there will be no further investment in photovoltaic energy, wind energy, hydro pumps, or lithium batteries.

3.4.1. Objective Function

In the context of the project, the objective function represents the optimization goal that is aimed to achieve. Specifically, the goal is to minimize the cost associated with the dispatched electrical energy while ensuring that the energy production meets the demand. Achieving this balance is crucial for the sustainability and efficiency of energy systems.

Moreover, the structure of the objective function provides valuable insights into how different components within the system interact. It reveals the relationships and dependencies among these components, helping to understand how changes in one part of the system can impact overall performance and costs. This understanding is essential for developing strategies that optimize the entire system, rather than just individual parts.

As formulated in the equation (11 , the objective function for the Economic Dispatch model considers the following five components:

$$\min \sum_{t=1}^{8760} \left(\sum_{g=1}^{NG_W} C_W * v_W[g,t] + \sum_{g=1}^{NG_{PV}} C_{PV} * v_{PV}[g,t] + \sum_{g=1}^{NG_{TH}} \left(C_{TH} * v_{TH}[g,t] + c_{th_{su}}[g,t] + c_{th_{sd}}[g,t] \right) + \sum_{g=1}^{NG_N} C_N * v_N[g,t] + C_{ENS} * v_{ens}[t] \right) \quad (1)$$

- **C_W** represents the cost per unit of energy from wind generation, and **$v_W(g, t)$** 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.
- **C_{PV}** is the cost per unit of energy from PV generation, and **$v_{PV}(g, t)$** is the volume of energy produced by the PV generator. The multiplication of the two represents the cost of energy generated by photovoltaic generators.
- **C_{TH}** is the cost per unit of energy from Thermal generation, and **$v_{TH}(g, t)$** is the volume of energy produced by the thermal generators. The multiplication of the two represents the cost of energy generated by nuclear generators. Also, C_{TH_SD} and C_{TH_SU} represent the costs of start-up and shut down of the generators.
- **C_N** is the cost per unit of energy from Nuclear generation, and **$v_N(g, t)$** is the volume of energy produced by the nuclear generator. The multiplication of the two represents the cost of energy generated by nuclear generators
- **$C_{ENS} \times v_{ENS}(t)$:** Lastly, this term covers the cost of any energy not supplied (ENS). C_{ENS} is the cost associated with each unit of unserved energy, and $v_{ENS}(t)$ is the volume of energy not supplied in each interval.

3.4.2. Power Balance Constraint

The first constraint that will be mentioned is the Power Balance constraint (2). This constraint is in charge of controlling that the demand is matched with the energy offer, taking into consideration all the generators that affect the model.

The constraint can be represented as follows:

$$\sum_{g=1}^{NG_W} v_W[g,t] + \sum_{g=1}^{NG_{PV}} v_{PV}[g,t] + \sum_{g=1}^{NG_{TH}} (v_{TH}[g,t]) + \sum_{g=1}^{NG_N} v_{PV}[g,t] + v_{ens}[t] = Q_D[t] \quad \forall\, t \tag{2}$$

- **Q_D[t]**: The demand of the system per hour

The power balance constraint is crucial in the economic dispatch model, primarily ensuring system reliability. Its core principle is maintaining equilibrium between supply and demand.

Moreover, this constraint refines the 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 theoretically possible but practically unfeasible solutions, thereby avoiding disruptions to the power supply-demand balance.

3.4.3. Generators' Constraints

In this subsection, the different constraints that apply to each one of the generators will be presented. Some of these constraints are the power limit of the generators or the start-up and shut-down processes in the thermal generators.

Photovoltaic Generator

The Photovoltaic Generator has only one constraint regarding the amount of power it can produce per hour. The energy produced cannot be greater than its capacity at any time, as this could create an unfeasible solution. Thus, this is the shape of the constraint:

$$v_{pv}[g,t] \le Q_{PV} * Q_{PV_{norm}}[g,t] \quad \forall\, t, g \tag{3}$$

Where v_{pv} is the value of the energy produced per hour and per generator, Q_{pv} is the installed capacity per generator in this model and Q_{PVnorm} is the normalized shape of the total production of the solar energy per hour. The capacity refers to the capacity mention in section 3.2 of 19.785 MW [8].

Wind Generator

The Wind Generator has only one constraint regarding the amount of power it can produce per hour. The energy produced cannot be greater than its capacity at any time, as this could create an unfeasible solution. Thus, this is the shape of the constraint:

$$v_W[g,t] \leq Q_W * Q_{W_{norm}}[g,t] \quad \forall\, t, g \tag{4}$$

Where v_w is the value of the energy produced per hour and per generator, Q_w is the installed capacity per generator in this model and Q_{Wnorm} is the normalized shape of the total production of the solar energy per hour. The capacity refers to the capacity mention in section 3.2 of around 30 GW [9].

Nuclear Generator

The Nuclear Generator has two constraints regarding the amount of power it can produce per hour. As this type of generators tend to be used as base generators, they cannot be turned on or off at any time. Thus, for this project, it has been decided that the nuclear power will be operating between the 90% of its capacity and the full capacity output. For that, the next constraints have been modelled:

$$v_N[g,t] \leq Q_N, \quad \forall\, t, g \tag{5}$$

$$v_N[g,t] \geq 0.9 * Q_N, \quad \forall\, t, g \tag{6}$$

Where v_N is the value of the energy produced per hour and per generator and Q_N is the installed capacity per generator in this model. This value refers to the capacity mention in section 3.2 of around 7 GW [10].

Thermal Generators

The Thermal Generators in this model are going to be used as peak generation, meaning that they will only be needed to operate when the other generators cannot supply the specific demand for one hour. As mentioned in section 3.2, these generators will be modelled as 25 generators with an increasing operating cost. They will also be modelled with start-up and shut-down costs that will try to represent the reality of this type of generators as best as possible and will also have a minimum of operation that will consist in the 10% of the maximum capacity of the generator. Taking all this into account, these are the first constraints that apply to the Thermal Generators:

$$v_{TH}[g,t] \leq Q_{TH} * u_{on}[g,t] \; \forall \; g, \qquad t \tag{7}$$

$$v_{TH}[g,t] \geq 0{,}1 * Q_{TH} * u_{on}[g,t] \; \forall \; g, \qquad t \tag{8}$$

Where v_{TH} is the value of the energy produced per hour and per generator and Q_{TH} is the installed capacity per generator in this model. This value refers to the capacity mention in section 3.2 of around 1 GW.

Now, the start-up and shut-down constraints are presented:

$$on_{TH}[g,t] - off_{TH}[g,t] = u_{on}[g,t] - u_{on}[g,t-1] \; \forall \; g, \qquad t > 1 \tag{7}$$

$$on_{TH}[g,t] - off_{TH}[g,t] = u_{on}[g,t] \; \forall \; g, t = 0 \tag{8}$$

$$c_{th_{su}}[g,t] = C_{TH_{SU}} * on_{TH}[g,t] \; \forall \; g, \qquad t \tag{9}$$

$$c_{th_{sd}}[g,t] = C_{TH_{SD}} * off_{TH}[g,t] \; \forall \; g, \qquad t \tag{10}$$

The first two equations represent how the algorithm calculates if a certain generator is turned on or off. These constraints are essential for the correct function of the thermal generators. The variable u_{on} is a binary variable that represents whether a generator is producing energy or not. Thus, the variables on_{th} and off_{th} store if there has been a change in the generator regarding the last period of time, allowing the shut-down and start-up costs to be included in the objective function for that specific generator and period of time through the variables c_{thsu} and c_{thsd}.

3.5. Investment model

This subsection will dive into the Investment Model, which is one of the main goals of this project. The idea of it will be to match the electricity demand with the power supplied by the different generator types previously mentioned while being able to invest in renewable technologies such as photovoltaic, wind, hydro pump and lithium batteries. This model is based on the previous one and thus, both models will have similarities at every level.

3.5.1. Objective Function

In the context of the project, the objective function represents the optimization goal that is aimed to achieve. Specifically, the goal is to minimize the cost associated with the dispatched electrical energy plus the investment cost in new technology expansions.

Thus, for this investment model the shape of the objective function (11) will slightly change regarding the Economic Dispatch Model, the inclusion of new investment variables leaves the objective function with this shape:

$$
\begin{aligned}
min \sum_{t=1}^{8760} \Bigg(& \sum_{g=1}^{NG_W} C_W * v_W[g,t] + \sum_{g=1}^{NG_{PV}} C_{PV} * v_{PV}[g,t] \\
& + \sum_{g=1}^{NG_{TH}} \left(C_{TH} * v_{TH}[g,t] + c_{th_{su}}[g,t] + c_{th_{sd}}[g,t] \right) \\
& + \sum_{g=1}^{NG_N} C_N * v_{PV}[g,t] + C_{ENS} * v_{ens}[t] + INV_{PV} * inv_{pv} \\
& + INV_W * inv_w + INV_{25} * inv_{25} + INV_{11} * inv_{11} \\
& + Fixed_{batt1} * inv_{11} + Variable_{batt1} * p_{out11}[t] \\
& + Fixed_{batt2} * inv_{25} + Variable_{batt2} * p_{out25}[t] + C_{ENS} \\
& * v_{ENS}[t] \Bigg)
\end{aligned}
\qquad (11)
$$

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 v_W(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.

- **C_{PV}** is the cost per unit of energy from PV generation, and $v_{PV}(g, t)$ is the volume of energy produced by the PV generator. The multiplication of the two represents the cost of energy generated by photovoltaic generators.
- **C_{TH}** is the cost per unit of energy from Thermal generation, and $v_{TH}(g, t)$ is the volume of energy produced by the thermal generators. The multiplication of the two represents the cost of energy generated by nuclear generators. Also, C_{TH_SD} and C_{TH_SU} represent the costs of start-up and shut down of the generators.
- **C_N** is the cost per unit of energy from Nuclear generation, and $v_N(g, t)$ is the volume of energy produced by the nuclear generator. The multiplication of the two represents the cost of energy generated by nuclear generators.
- **$INV_{PV} \times inv_{PV}$:** this multiplication calculates the total cost of investment in photovoltaic power that will suppose the new inclusion of MW adding it to the one that currently existed in the model.
- **$INV_W \times inv_W$:** this multiplication calculates the total cost of investment in wind power that will suppose the new inclusion of MW adding it to the one that currently existed in the model.
- **$INV_{25} \times inv_{25}$:** this multiplication calculates the total cost of investment in lithium batteries that will suppose the new inclusion of MW of this storage system in the model.
- **$INV_{11} \times inv_{11}$:** this multiplication calculates the total cost of investment in hydro pumps that will suppose the new inclusion of MW of this storage system in the model.
- **$Fixed_{batt1}*inv_{11}+Variable_{batt1}*p_{out11}[t]$:** This term is in charge of the total operating cost for the hydro pump batteries. It consists of two different types of costs. The first one depends only on the installed capacity of the hydro pump storage system and the second one depends on the amount of energy that will be produced with it.
- **$Fixed_{batt2}*inv_{25}+Variable_{batt2}*p_{out25}[t]$:** This term is in charge of the total operating cost for the lithium batteries. It consists of two different types of costs. The first one depends only on the installed capacity of the hydro pump storage system and the second one depends on the amount of energy that will be produced with it.

- **C_{ENS} × v_{ENS}(t):** Lastly, this term covers the cost of any energy not supplied (ENS). C_{ENS} is the cost associated with each unit of unserved energy, and v_{ENS}(t) is the volume of energy not supplied in each interval.

3.5.2. Power Balance Constraint

The first constraint that will be mentioned for this model is the Power Balance constraint (12). This constraint oversees controlling that the demand is matched with the energy offer, taking into consideration all the generators that affect the model.

The constraint can be represented as follows:

$$\sum_{g=1}^{NG_W} v_W[g,t] + \sum_{g=1}^{NG_{PV}} v_{PV}[g,t] + \sum_{g=1}^{NG_{TH}} (v_{TH}[g,t]) + \sum_{g=1}^{NG_N} v_{PV}[g,t] + p_{out11}[t] - p_{in11}[t] + p_{out25}[t] - p_{in25}[t] + v_{ens}[t] = Q_D[t], \quad \forall\, t \qquad (12)$$

The new additions that exist in this model are the storage system terms. There are two different types. The ones that have the suffix out mean that the battery produces energy and gives it to the system. The others that have the suffix in represent the amount of energy being stored in the battery, for an easier understanding, this works as another demand different than the one that comes from the grid.

3.5.3. Generators' Constraints

In this section, the different constraints that apply to each one of the generators will be presented. These constraints help the model to be more realistic and prevents the model from having wrong solutions. Some of these constraints are the power limit of the generators or the start-up and shut-down processes in the thermal generators.

Photovoltaic Generator

The Photovoltaic Generator has only one constraint regarding the amount of power it can produce per hour. The energy produced cannot be greater than its capacity at any time, as this could create an unfeasible solution. Thus, this is the shape of the constraint:

$$v_{pv}[g,t] \leq (Q_{PV} + inv_{pv}) * Q_{PV_{norm}}[g,t] \quad \forall\, t, g \qquad (13)$$

Where v_{pv} is the value of the energy produced per hour and per generator and Q_{pv} is the installed capacity per generator in this model and Q_{PVnorm} is the normalized shape of the total production of the solar energy per hour. The capacityrefers to the capacity mention in section 3.2 of 19.785 MW [8]. The new term that appears in this model is inv_{pv}, which is the amount of new installed capacity that will appear with the new investments.

Wind Generator

The Wind Generator has only one constraint regarding the amount of power it can produce per hour. The energy produced cannot be greater than its capacity at any time, as this could create an unfeasible solution. Thus, this is the shape of the constraint:

$$v_W[g,t] \leq (Q_W + inv_w) * Q_{W_{norm}}[g,t] \quad \forall\, t, g \qquad (14)$$

Where v_w is the value of the energy produced per hour and per generator, Q_w is the installed capacity per generator in this model and Q_{Wnorm} is the normalized shape of the total production of the solar energy per hour. The capacity refers to the capacity mention in section 3.2 of around 30 GW [9]. The new term that appears in this model is inv_w, which is the amount of new installed capacity that will appear with the new investments.

Nuclear Generator

The Nuclear Generator has two constraints regarding the amount of power it can produce per hour. As this type of generators tend to be used as base generators, they cannot be turned on or off at any time. Thus, for this project, it has been decided that the nuclear power will be operating between the 90% of its capacity and the full capacity output. For that, the next constraints have been modelled:

$$v_N[g,t] \leq Q_N \qquad (15)$$

$$v_N[g,t] \geq 0.9 * Q_N \qquad (16)$$

Where v_N is the value of the energy produced per hour and per generator and Q_N is the installed capacity per generator in this model. This value refers to the capacity mention in section 3.2 of around 7 GW [10].

Thermal Generators

The Thermal Generators in this model is the same as it was described in section 3.4.3.

Hydro Pump Storage

The Hydro Pump Storage in this model will be used as a storage system that will allow the total cost of the system to be reduced as it will be able to reduce the curtailments that can take place during some parts of the year because of an excess in the amount of photovoltaic or wind energy produced. For modelling this storage system, the State of Charge (SOC) will be used, along with several other constraints and variable.

Thus, this is how the modelling of the system is presented:

$$SOC_{11}[t] \leq inv_{11} * relation1 \quad \forall\, t \tag{17}$$

$$SOC_{11}[t] \geq 0{,}2 * inv_{11} * relation1 \quad \forall\, t \tag{18}$$

These two equations model the limits of the State of Charge for the hydro pump in this model. The upper limit is the relation that the hydro pump system has between MW and MWh which has been modelled as 30h. The lower limit has a restriction of the 20% of the total possible value, this allows the battery to always have at least the 20% of the energy in reserve, giving it a sense of reality.

The next two constraints model the power limits of the storage system:

$$p_{out_{11}}[t] \leq inv_{11} \quad \forall\, t \tag{18}$$

$$p_{in_{11}}[t] \leq inv_{11} \quad \forall\; t \tag{19}$$

These two constraints allow the hydro pump to offer feasible solutions in terms of the amount of power produced and received per hour as this value cannot exceed the power limits of the pump that, in this case, will be determined by the amount of investment decided by the model.

Now that the limits have been set for the SOC and the power for the hydro pump, the only thing left to fully determine a storage system is the value that the SOC is going to have at every moment. For that, the next equations are presented:

$$SOC_{11}[t] = 0{,}2 * inv_{11} * relation1, \quad t = 0 \tag{20}$$

$$SOC_{11}[t] = SOC_{11}[t-1] - \frac{p_{out_{11}}[t]}{efficiency1} + p_{in_{11}}[t] * efficiency1 \quad \forall\, t \geq 1 \tag{21}$$

In these constraints, it is important to address the importance of the efficiency. This efficiency allows the hydro pump model to be more realistic, as this type of storage systems always have losses when they gain energy and when they give it to the grid.

The first constraint means that the hydro pump starts with the 20% of its capacity stored, as it has been stated, this is the lower limit. The second constraint on the other hand, is a combination of values which means that the SOC at a certain hour is the SOC of the previous hour minus the amount of energy that is going to be poured to the system and plus the excess of energy that can be stored in the hydro pump to be used in the next hours.

Finally, an additional constraint modelled the fact that batteries cannot give energy while storing it. Thus, during one period of time (t), the battery will either produce energy to meet a portion of the demand or it will act as a "new demand" reducing the potential curtailments which could appear due to the excessive production of wind or solar power. The idea behind the next constraint is based on the fact that batteries normally operate on full power, meaning that it uses all the capacity that it has to give energy or to store. Thus, with next constraint as the limit is going to be the capacity, the batteries will tend to only give energy or store it, rather than both things at the same time

$$P_{out_{11}}[t] + P_{in_{11}}[t] \leq inv_{11} + \text{capacity}_{11} \tag{22}$$

The variables used in this equation represent the amount of energy entering and leaving the battery on the left side. On the right side, on variable represents the investment variable and the other represents the initial capacity of the battery (the value of this parameter will be zero for the model).

Lithium Battery Storage

The Lithium Battery Storage in this model will be used as a storage system that will allow the total cost of the system to be reduced as it will be able to reduce the curtailments that can take place during some parts of the year because of an excess in the amount of photovoltaic or wind energy produced. For modelling this storage system, the State of Charge (SOC) will be used, along with several other constraints and variable.

Thus, this is how the modelling of the system is presented:

$$SOC_{25}[t] \leq inv_{25} * relation2 \quad \forall\, t \tag{23}$$

$$SOC_{25}[t] \geq 0{,}2 * inv_{25} * relation2 \quad \forall\, t \tag{24}$$

These two equations model the limits of the State of Charge for the hydro pump in this model. The upper limit is the relation that the hydro pump system has between MW and MWh which has been modelled as 4h. The lower limit has a restriction of the 20% of the total possible value, this allows the battery to always have at least the 20% of the energy in reserve, giving it a sense of reality.

The next two constraints model the power limits of the storage system:

$$p_{out_{25}}[t] \leq inv_{25} \quad \forall\, t \tag{25}$$

$$p_{in_{25}}[t] \leq inv_{25} \quad \forall\, t \tag{26}$$

These two constraints allow the lithium battery to offer feasible solutions in terms of the amount of power produced and received per hour as this value cannot exceed the power limits of the pump that, in this case, will be determined by the amount of investment decided by the model.

Now that the limits have been set for the SOC and the power for the lithium battery, the only thing left to fully determine a storage system is the value that the SOC is going to have at every moment. For that, the next equations are presented:

$$SOC_{25}[t] = 0{,}2 * inv_{25} * relation2, \quad t = 0 \tag{27}$$

$$SOC_{25}[t] = SOC_{25}[t-1] - \frac{p_{out_{25}}[t]}{efficiency2} + p_{in_{25}}[t] * efficiency2 \quad \forall\, t > 1 \tag{28}$$

In these constraints, it is important to address the importance of the efficiency. This efficiency allows the lithium battery model to be more realistic, as this type of storage systems always have losses when they gain energy and when they give it to the grid.

The first constraint means that the lithium battery starts with the 20% of its capacity stored, as it has been stated, this is the lower limit. The second constraint on the other hand, is a combination of values which means that the SOC at a certain hour is the SOC of the previous hour minus the amount of energy that is going to be poured to the system and plus the excess of energy that can be stored in the lithium battery to be used in the next hours.

Finally, there has been an additional constraint that modelled the fact that batteries cannot give energy while storing it. Thus, during one period of time (t), the battery will either produce energy to meet a portion of the demand or it will act as a "new demand" reducing the potential curtailments which could appear due to the excessive production of wind or solar power.

$$P_{out_{25}}[t] + P_{in_{25}}[t] \leq inv_{25} + \text{capacity}_{25} \quad (29)$$

The variables used in this equation represent the amount of energy entering and leaving the battery on the left side. On the right side, on variable represents the investment variable and the other represents the initial capacity of the battery (the value of this parameter will be zero for the model).

3.6. Calculation of Marginal Prices with group start-up constraints and uplifts

The idea of this section is to briefly explain how the Marginal Prices have been obtained from the models in order to analyze the profitability of each of the generators, making both models economically sustainable.

First, after having solved the optimization problem, the marginal prices are obtained for each hour. As it has been mentioned before, the Marginal Prices are the cost of producing one additional unit of electricity, typically measured in megawatt-hours (MWh). Marginal prices are used to determine the price at which electricity is bought and sold in wholesale electricity markets. Second, once these values have been obtained, they serve as the price at which electricity would be sold, so they are used and compared against the cost of production that every single generator has. Finally, it has been decided that if any generator has losses, an uplift is applied to this generator throughout all the hours it is used as the most expensive generator producing electricity. Thus, the generator won't produce losses or gains.

The equation used for obtaining the profitability of the nuclear, solar and wind power is:

$$Profit = (Marginal\ Price - Production\ Cost) * Energy \tag{30}$$

$$Profit = (Marginal\ Price - Prod.Cost) * Energy - SU_{TH} * on_{th} - SD * off_{th} \tag{31}$$

For the thermal generators, the start-up and shut-down costs are included along with the binary variables that tell if the generator has been turned on or off that hour:

The uplift technique is an adjustment added to wholesale electricity prices to cover all costs. These costs often include those related to ensuring the reliability and stability of the power grid. The main purpose of uplift charges is to provide a fair and transparent method for recovering these necessary but otherwise uncompensated costs.

Understanding these steps, in the next graph, it is possible to see the flow which the model follows in order to understand the economic side of the results obtained.

Figure 7. Profitability Flow of the Model

4. Results

This chapter is going to be divided into three different sections. First, the results of the Economic Dispatch Model will be presented and analyzed. Second, the Investment Model incorporating the new technologies will be studied. Finally, a number of different cases of the investment model with different sensitivities will be compared.

Furthermore, it is important to highlight that, to gain detail of what is happening during the year, it has been decided that in order to distinguish the changes between time periods, each of the results for the different technologies are going to be summed into four graphs that contain 15-days periods from the four different seasons (winter, spring, summer, and fall). Thus, these will be representative of the rest of the year. On the other hand, when analyzing the economic performance of the model, the absolute value of the whole year will be considered.

4.1.Economic Dispatch Model

4.1.1. Renewable Energy Dispatch

As it has been presented in section 3.2.2, there are only four generation technologies in this model: solar, wind, nuclear, and backup thermal. The first results that will be analyzed are the production of renewable technologies (solar and wind) with their curtailments throughout the year.

In Figure [8], it is possible to see how solar energy generation varies from season to season. As it is represented, during the summer season, the amount of energy dispatched is bigger than in the rest of the seasons, reaching almost 14.000 MW of power dispatched during the daylight hours, being winter, the season with less consumption of solar energy due to a lack of production caused by weather conditions. It is important to mention that this technology only is able to produce energy during daylight hours, and that is the reason behind the valleys in the shape of the curve.

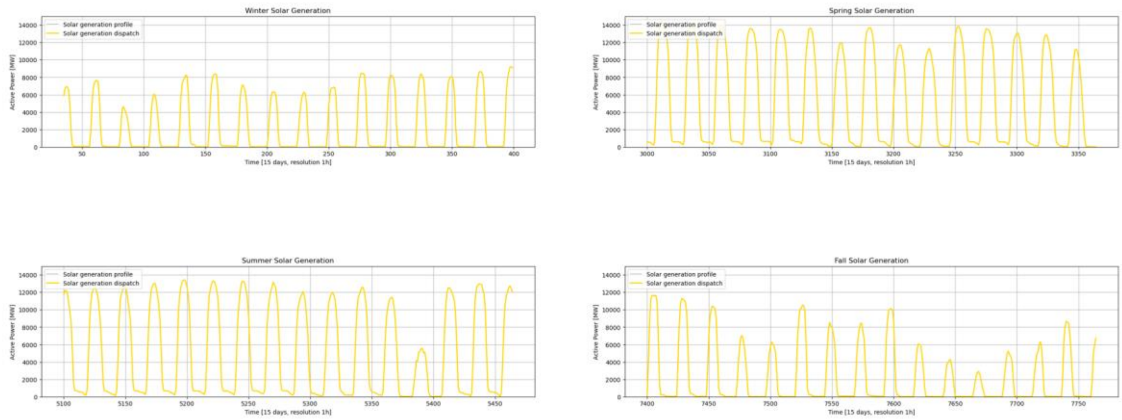

Figure 8. Solar Power Generation for EDM

When analyzing renewable energy, it is important to understand the curtailments, which is the amount of energy that could be produced but is being wasted because, at the time of the production, the demand cannot consume it. For that reason, the curtailments of solar energy are shown in the next graphs. In this model, as it can be seen in Figure [9], there are no curtailments of solar power. The lack of curtailments has to do with the fact this technology is the cheapest in terms of energy production and every energy that it produces is being consumed by the demand.

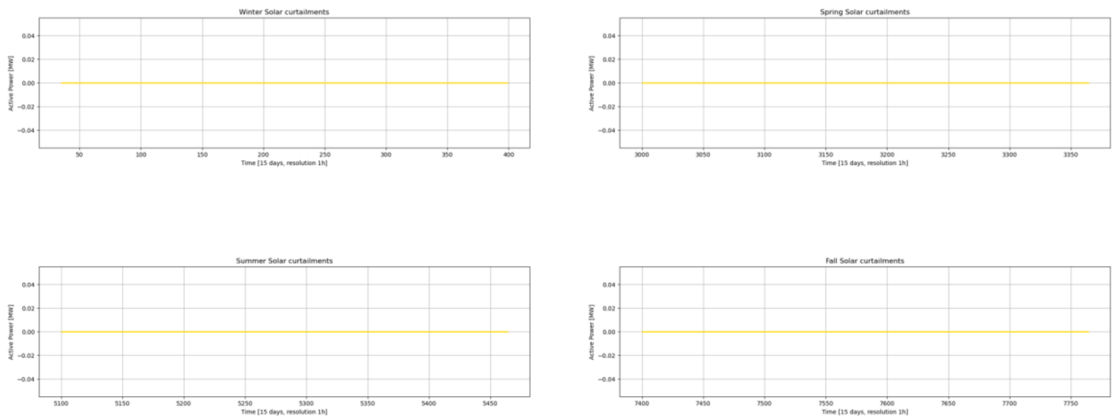

Figure 9. Solar Power Curtailments for EDM

The next technology that is going to be analyzed is the wind power. With this power source appears a change in the shape of the production curve compared to the solar power. It can be seen how the spring and specially the fall are the seasons in which more power is produced compared to the other two. It is also important to consider that there are more installed megawatts of wind power than solar but as it is a more expensive technology, if there is solar power being used there will be curtailments. That is the reason of why the wind power is mostly being used during nighttime, producing the valleys in the shape of the graph.

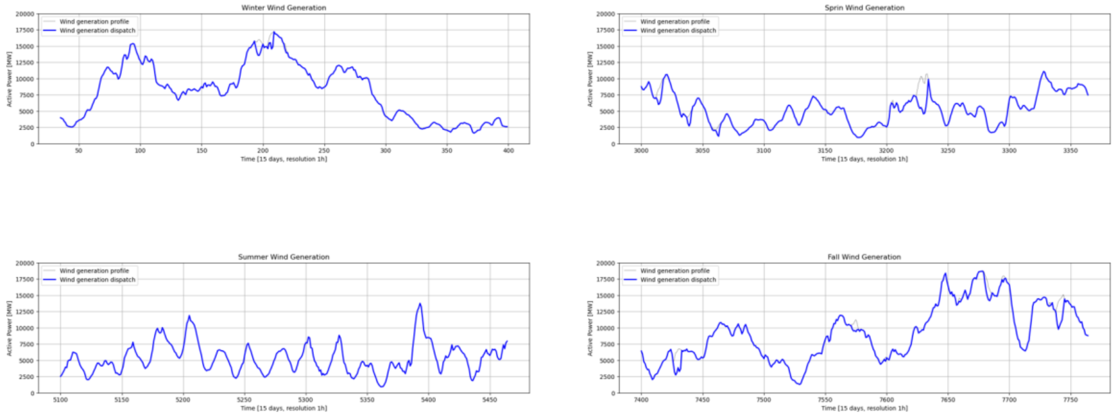

Figure 10. Wind Power Generation for EDM

Considering the curtailments of this power, it is important to see how these curtailments appear during daylight hours mostly as the solar power is being used. As with the solar power, the use of batteries makes sense in order to reduce the amount of these curtailments and to reduce the total cost of the system, as having the possibility of storing energy will prevent the use of more expensive technologies such as the back-up thermal generators.

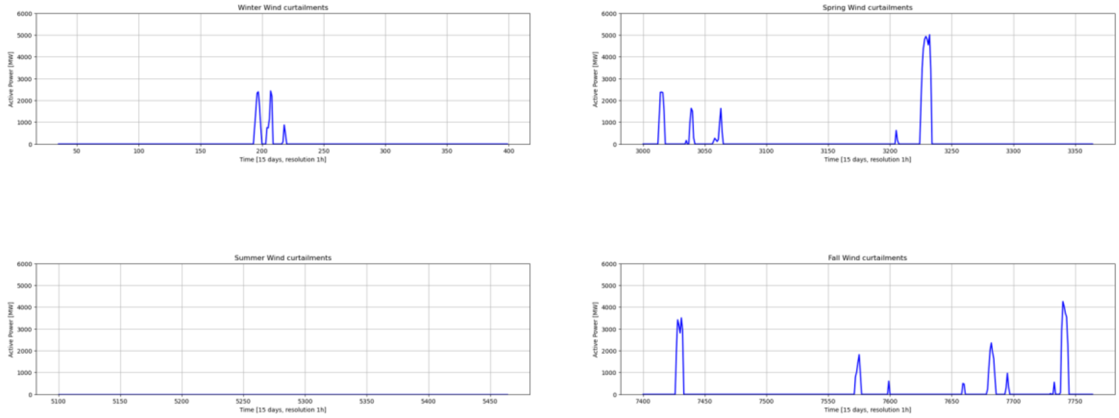

Figure 11. Wind Power Curtailments for EDM

4.1.2. All energy sources production compared with the demand

In Figure 12, the production of all energy sources is presented along with the total demand during that period of time. This allows to have an idea of which technologies are producing more energy and what is the importance of the renewable energy in this model.

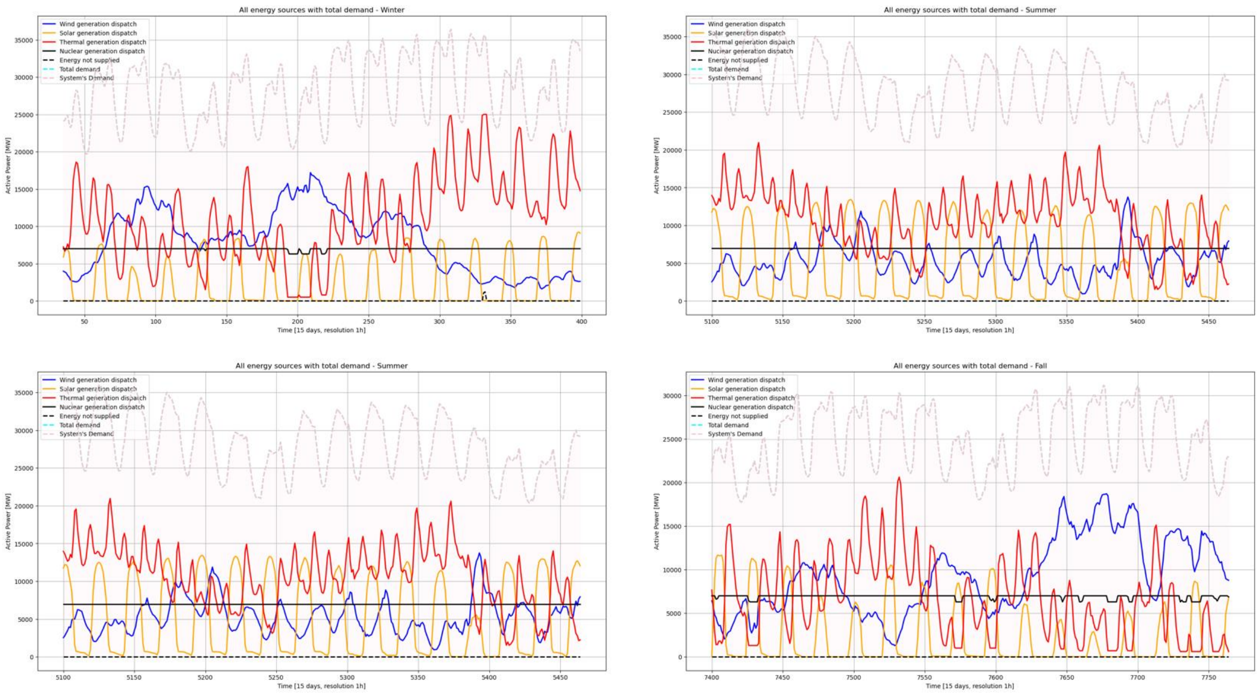

Figure 12. All energy sources compared with the Demand

Comparing the different seasons presented in Figure 12 (top left winter, top right spring, bottom left summer and bottom right fall), it is possible to put into perspective the results analyzed in the last section. During the winter, for example, it is shown that, as the solar power is low because of the weather conditions, the days when the wind does not produce a lot of energy, the system needs to rely on the thermal energy; thus, making the cost higher. On the other hand, during the summer the peaks of consumption of thermal energy are limited to the night hours, as the solar power increases its production and can cover a higher proportion of the total demand.

During the mid seasons, fall and spring, there is a combination of the previous ones. The solar power production is relevant during the daytime, but it is in the wind where the key of the model relies on. For example, during the fall, the wind reduces the cost of the system during the last part shown in the figure, while in the first hours shown, the wind decreases, making the thermal energy again produce an important part of the demand.

For this model, there is no one important technology that covers the majority of the demand. Nuclear is the most reliable technology as it operates on a constant basis, while wind and solar power are technologies that depend on weather conditions. It is clear that, for this model, thermal energy plays a pivotal role, producing a large amount of energy that meets the demand in all the seasons of the year.

In Figure 13 the comparison between technologies is clearer. As mentioned before, the nuclear energy (the cyan one) is constant throughout the whole year, being used as a base energy source. The variations of renewable energy can be put into perspective as well; during the summer for the solar or during the fall for the wind power, the energy produced is bigger, helping the thermal energy to have a less important role. Another important aspect of the model that this Figure helps to understand is how the thermal energy tends to be used during the valley nights.

Finally, it can also be seen a small amount of energy is not supplied during the winter, a period with a small amount of renewable energy. This happens at some hours during the whole year in this model, and it affects the marginal prices and the cost of the system.

4.1.3. Cost Analysis

Before analyzing the marginal costs of the model, it makes sense to understand the global picture, understanding the total amount of production per technology and their costs. For that, these parameters are presented in the Table 11.

	Total Energy Dispatched (MWh)	Total Cost (€)	Average Cost per MWh (€/MWh)
Nuclear	61.016.277	1.403.374.371	23,00
Wind	58.223.834	582.238.342	10,00
Solar	31.091.866	155.459.333	5,00
Thermal	85.743.063	4.251.259.622	49,58
ENS	21.084	166.141.920	7.880,00
TOTAL	**236.096.125**	**6.558.473.588**	**27,78**

Table 11. Total Dispatch and Cost per Technology

Looking into Table 11, it is clear that the technologies that are producing the most amount of energy are nuclear, because it has a very constant production throughout the whole year, and thermal energy because it is in charge of covering all the demand that the rest of technologies cannot cover. Renewable technologies have an important impact, being around 40% of the total demand, but they are far from reaching 80% of green energy, which is the Spanish goal by 2030.

Another important insight to take from Table 11 is that the thermal energy, despite being only 36% of the total energy dispatched, its cost represents 64% of the total cost produced to cover the demand. For the investment model, one of the goals is to reduce the importance of the thermal energy in the system, trying to use it as a real back-up energy source rather than a pivotal one.

Having all this information, the next point to analyze is the Marginal Costs of the model and how they vary along with the seasons during the year. In Figure 14, the graph shown represents the marginal cost curve of the model throughout the year, being the average value 42,37 €/MWh.

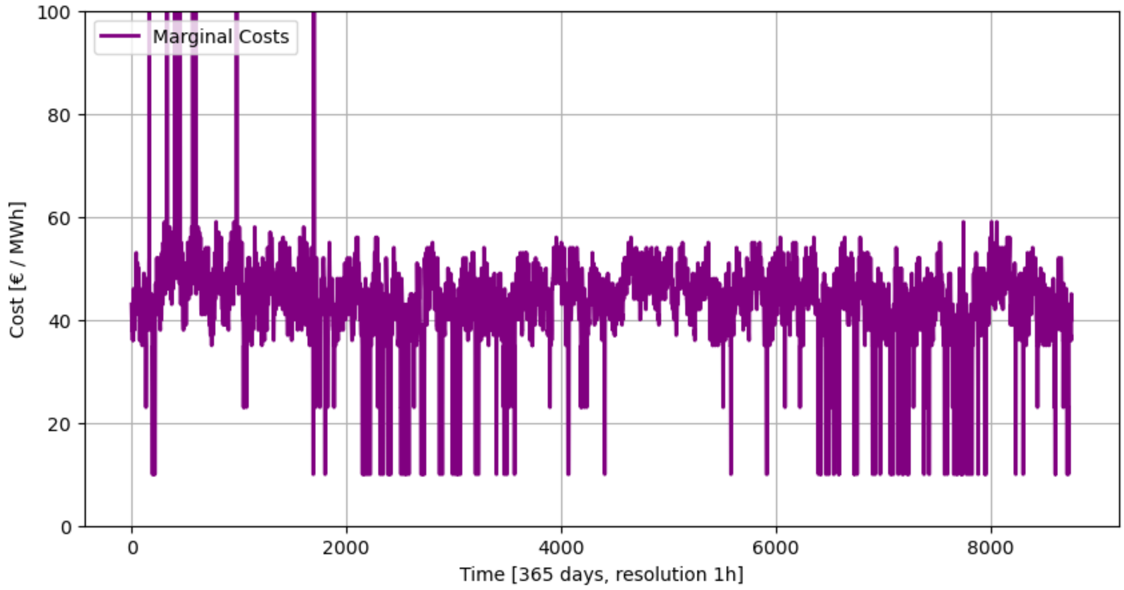

Figure 14. Marginal Costs for the EDM

From this picture, many of the insights that have been mentioned before can be reaffirmed. The first one is that, during the spring and fall seasons, the wind has a key role in reducing the cost of the model, as it can be seen how (mainly during the day) the marginal costs go down to 10 €/MWh thanks to the large production of wind energy. On the other hand, during the rest of the year, thermal energy sets the marginal cost of the system. Solar energy, as it does not have the amount of installed capacity needed, cannot establish its cost as the marginal price. Thus being the most profitable technology of all four.

Finally, some energy is not supplied during the winter season. This happens because the lack of solar power during those months, which added to the lack of wind on some days during the winter. Despite this, as it has been shown, the number of MWh of energy not supplied is very small, not even reaching 0,01% of the total energy dispatched during the year.

4.1.4. Generator profits and market price uplifts

The goal of this section is to analyze and obtain key insights into the profitability per generator used in the model. There are 27 generators: 1 equivalent solar generator, 1 equivalent wind generator, 1 equivalent nuclear generator, and 24 thermal generators. The profitability will be studied by comparing the production costs against the market revenues determined by the marginal prices and generator productions mentioned and analyzed before in the document.

Taking all this into consideration, these are the profitability results for the model's generator in the Economic Dispatch Model:

Total Profit (€)	Generator	Total Profit (€)	Generator
1.055.353.273	PV	195.103.800	Thermal_11
2.451.999.779	Wind	192.221.900	Thermal_12
2.507.758.400	Nuclear	190.024.900	Thermal_13
262.482.900	Thermal_0	180.433.500	Thermal_14
254.412.700	Thermal_1	179.360.600	Thermal_15
246.589.800	Thermal_2	178.704.200	Thermal_16
239.021.800	Thermal_3	178.038.400	Thermal_17
231.776.000	Thermal_4	170.238.600	Thermal_18
224.967.300	Thermal_5	170.456.500	Thermal_19

218.619.800	Thermal_6	170.741.400	Thermal_20
212.757.100	Thermal_7	171.122.600	Thermal_21
207.441.900	Thermal_8	171.528.100	Thermal_22
202.772.900	Thermal_9	148.159.100	Thermal_23
198.605.400	Thermal_10	163.843.800	Thermal_24

Table 12. Generator's Profitability for the EDM

As it can be seen, there is no need to apply any uplift to any generator in this case study. Trying to deepen these results, the fact that none of the thermal generators needs it (these are the generators that could need an uplift due to the fact that are the last ones in use because of their production cost), comes because the number of hours where there is energy not supplied, especially during the winter, is high enough to make them profitable.

On the other hand, renewable energy generators, solar and wind, and nuclear generators have the highest profits due to the low production costs compared to thermal generators and the amount of energy produced during the year.

4.2.Investment Model

For the investment model, several cases are going to be analyzed involving different sensibilities and modifying parameters. In this subsection, the base case of the investment model is going to be analyzed. For that, the first thing is to describe and remember the variations of the model with regards to the Economic Dispatch Model.

Two new technologies are added to this system, including lithium batteries and the hydro pump as storage systems. These technologies had already been defined in previous sections of this thesis and won't have any installed capacity previously. Moreover, there are going to be some modifications in the input parameters that will define a new framework.

It has been decided that the cost of production of the thermal energy will increase from the range of [35, 60] € to [60, 85] €, thus a more than likely variation that can take place in the future regarding this technology will be modelled. The second variation of the parameters is the reduction of 50% of the nuclear installed capacity, going from 7000 MW to 3500 MW (this aligns with the intentions of the Spanish government of closing the majority of the nuclear installed capacity in Spain in the years to come).

Knowing all the modifications applied for the base case of the Investment Model, in the Table 13, the investment megawatts per technology decided by the optimization under the model are presented, so that it is possible to have a first image of the main results obtained.

Technology	Investment (MW)
Solar	33.483
Wind	21.018
Lithium Batteries	0
Hydro Pump	8.021

Table 13. Investment per Technology for the IM

From Table 13, the first conclusions of the model can be drawn. First, as the investment in solar power represents a 170% compared to the 19.785MW which were initially installed. Second, the new wind power is 21.018 MW, which are the 70% of the previous installed capacity. These two new investments mean that there was enough room for more renewable energy in the model. It is also remarkable that there is no investment in Lithium Batteries, as it will be drawn from the next sections. This happens because the model prefers to invest, when possible, in Hydro Pump, as this storage system allows the energy to be kept stored for a longer period of time.

Acknowledging all these factors, the presentation of the results will follow a similar organization as in the previous section, looking into the technologies, and diving into the economic analysis of the system.

4.2.1. All energy sources productions compared with the demand

In Figure 20, the production of all energy sources is presented along with the total demand. This allows to have an idea of which technologies are producing more energy and what is the importance of renewable energy in this model.

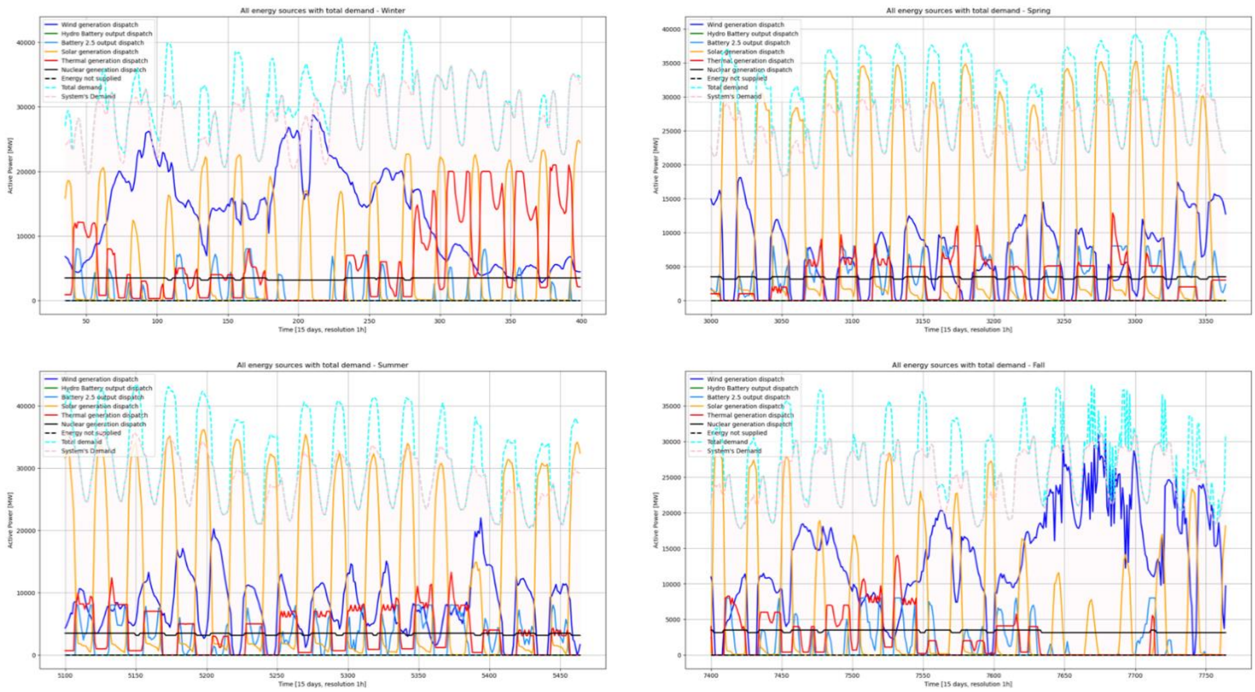

Figure 20. All energy sources compared with the Demand

In Figure 20, new technologies have been added, and thus, new curves are represented on the graphs. The cyan represents the addition of the demand curve and the power the hydro pump demands to store. Also, in light blue and with a smaller value, it is possible to see the power released by the hydro pump every hour.

Comparing the different seasons presented in Figure 20 (top left winter, top right spring, bottom left summer, and bottom right fall), the results analyzed in the last section can be put into perspective. During the winter, for example, it is shown that, as solar power is weak because of the weather conditions, on the days when the wind does not produce a lot of energy, the system needs to rely on thermal energy, thus making the cost higher. On the other hand, during the summer, the peak consumption of thermal energy is limited to the night hours, as solar power increases its production and can cover a higher proportion of the total demand.

During the fall season, there is a combination of the previous ones. The solar power is relevant during the daytime, but it is in the wind where the key of the model relies on. For example, during the fall, the wind reduces the cost of the system during the last part shown in the figure, while in the first hours shown, the wind decreases, making the thermal energy once again produce an important part of the demand.

For this model, there is no one important technology that covers the majority of the demand. While wind and solar power are technologies that depend on the weather conditions, it is clear that, for this model, they have increased their importance thanks to the new investment megawatts, providing the system with greener energy than in the initial Economic Dispatch Model with no investments.

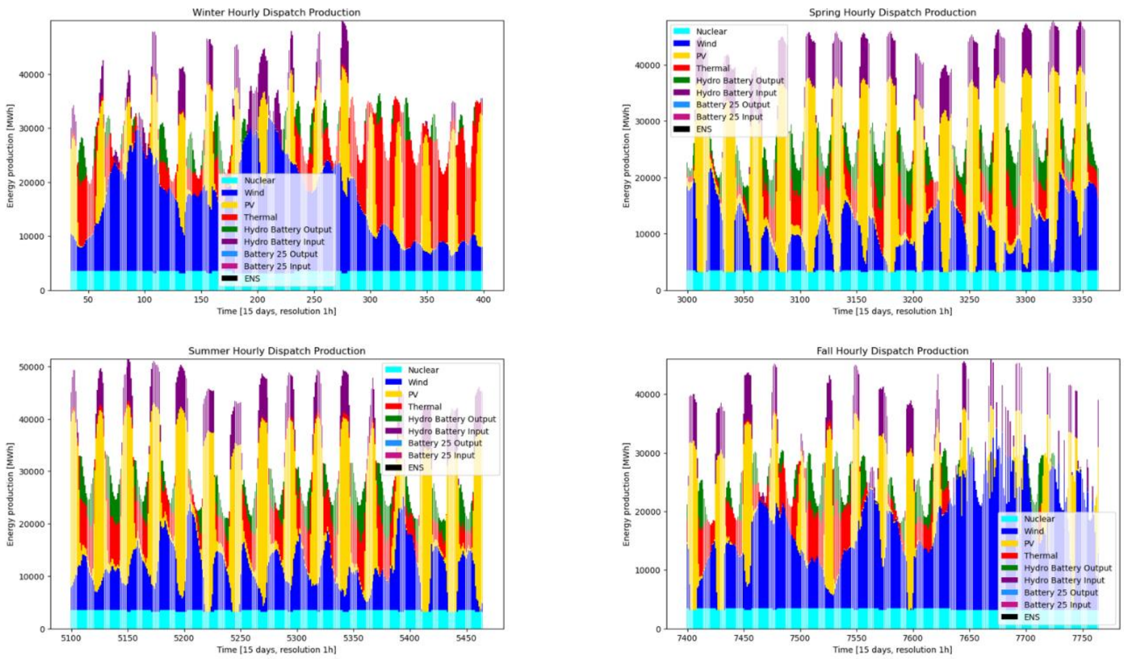

Figure 21. Power Generation for EDM

In Figure 21 the comparison between technologies is clearer. As mentioned before, the nuclear energy (the cyan one) is constant throughout the whole year but has lost importance as their installed capacity has been reduced by 50%. The variations of renewable energy can be put into perspective as well; during the summer for solar or during the fall for wind power, the energy produced is bigger, helping thermal energy to have less importance. Another important aspect of the model that this Figure helps to understand is how the thermal energy tends to be used during the valley nights.

The purple peaks represent the energy consumed by the hydro pump storage, which takes place during the day, as has been mentioned before, and the green part of the night valleys are the representation of the energy released by this technology. The way the hydro pump is working in this model makes perfect sense as it is consuming energy surplus during the day, and it is helping the model system to cut costs by reducing the need for backup thermal energy during the night.

To conclude this section, the change in the model with the new investments is clear. The solar and wind power have become the main forces in play and are allowing the model not to have the need of relying in the nuclear and thermal back-up anymore. Leaving these technologies to a secondary role, especially the thermal which its function is to only provide energy during the nights.

4.2.2. Cost Analysis

Before analyzing the marginal costs of the model, it makes sense to understand the global picture, knowing what the total amount of production per technology is and what their costs are regarding the investment. For that, in the next table, these parameters are presented.

	Total Energy Dispatched (MWh)	Total Cost (€)	Average Cost per MWh (€/MWh)
Nuclear	29.865.031,90	686.895.733,81	23,00
Wind	89.109.511,54	891.095.115,36	10,00
Solar	82.495.020,21	412.475.101,03	5,00
Thermal	39.506.665,80	1.943.993.142,03	49,21
Hydro Pump	14.636.971,07	43.910.913,22	3,00
Lithium Batteries	0,00	0,00	0,00
ENS	30,91	243.584,32	7.880,00
TOTAL	**255.613.231,44**	**6.717.452.276,81**	**26,28**

Table 14. Total Dispatch and Cost per Technology

Comparing Table 14 and Table 11, the technologies that are producing the most amount of energy have changed and now are wind and solar, because of the increase in their total installed capacities. Thermal and nuclear energy have lost importance and now only represent roughly 27% compared to the previous 60% they hold on to the Economic Dispatch Model with no investment. The hydro pump gains importance as well, being the cheapest technology in terms of operation costs. Finally, the ENS has decreased significantly as the total installed capacity has increased, and the storage system allows the model to have more than one backup system technology for when renewable energy cannot provide enough power due to weather conditions.

It is important as well to acknowledge that the hydro pump, even though it is the cheapest in terms of operating costs, has fixed costs that need to be covered as well. For that, in Table 15 the fixed costs for the storage systems are presented.

	Power (MW)	Total Fixed Cost (€)	Average Cost per MW (€/MW)
Hydro Pump	8.021,31	96.265.352,52	12.000,00
Lithium Batteries	0,00	0,00	0,00
TOTAL	**8.021,31**	**96.265.352,52**	**12.000,00**

Table 15. Fixed Costs for Storage Systems

The next costs that need to be analyzed are the investment costs per technology, these costs represent the annuity of the total investment in every technology both in absolute and per megawatt installed. The most expensive technology, as can be seen in Table 16, is the wind power followed by the hydro pump storage. The solar power, as it is the cheapest one to operate and invest is the one that has the biggest investment.

	New Power (MW)	Total Investment Cost (€)	Investment Cost (€/MW)
Wind	21.018	1.524.517.144	72.532
PV	33.483	1.214.321.542	36.266
Pump Batteries	8.021	514.352.102	64.123
Lithium Batteries	0,00	0,00	0,00

TOTAL	**62.523**	**3.253.190.789**	**52.031**

Table 16. Investment Costs per Technology for the IM

Having all this information, the next point to analyze is the Marginal Costs of the model and how they vary along with the seasons during the year. In the next figure, the graph shown represents the marginal cost curve of the model throughout the year. The average marginal cost for this model is 49,55 €/MWh

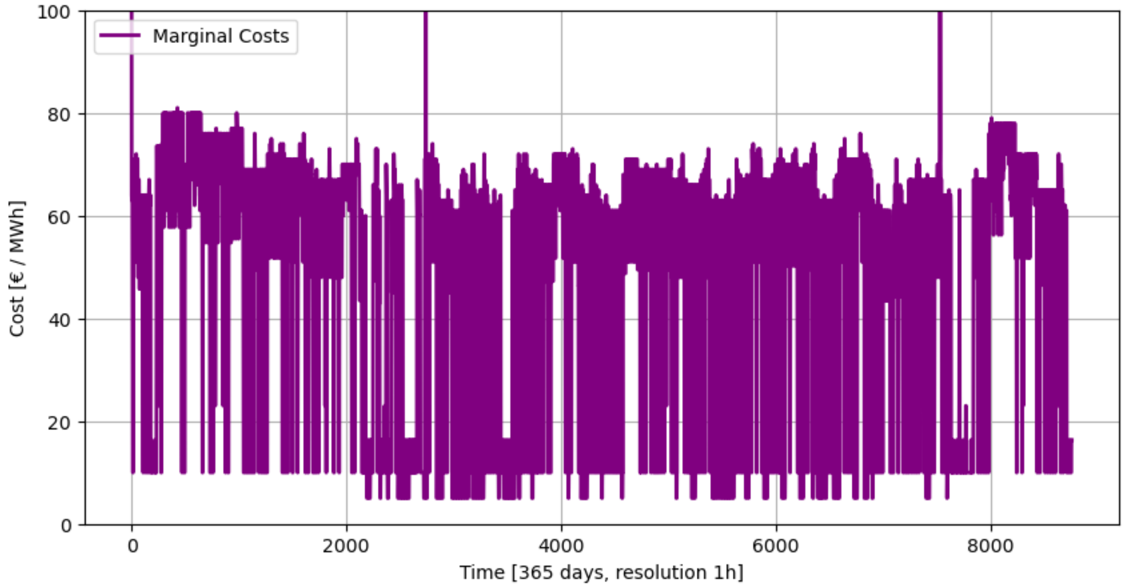

Figure 22. Marginal Costs for the EDM

From this picture a lot of the insights that have already been mentioned before can be reaffirmed. The first one is that the marginal costs compared to the Economic Dispatch Model have changed a lot; the inclusion of more renewable power has allowed the costs to reach many hours the value of 10 €/MWh during the year and even 5 €/MWh during the spring and summer seasons. On the other hand, during the rest of the year, the thermal energy is the one that sets the marginal cost of the model, especially during night hours throughout the whole year.

Finally, some energy is not supplied. This happens because of the lack of solar power during those hours, added to the lack of wind some days. Despite this, as it has been shown, the number of MWh of energy not supplied is very little, not even reaching 0,00001% of the total energy dispatched during the year.

4.2.3. Generator profits and market price uplifts

The goal of this section is to analyze and obtain key insights into the profitability per generator used in the model. There are 28 generators: 1 solar generator, 1 wind generator, 1 nuclear generator, the hydro pump generator and 24 thermal generators. The profitability will be studied by comparing the production costs against the market price revenues given by the marginal prices mentioned and analyzed before in the document.

Taking all this into consideration, these are the profitability results for the model's generator in the Economic Dispatch Model:

Total Profit	Technology	Total Profit	Technology
1.931.852.267,00	PV	9.628.819,00	Thermal_10
3.686.937.511,00	Wind	9.029.488,00	Thermal_11
879.470.865,00	Nuclear	8.866.102,00	Thermal_12
514.352.103,00	Hydro Pump	1.332.864,00	Thermal_13
-	Lithium Battery	149.708,00	Thermal_14
45.144.420,00	Thermal_0	150.336,00	Thermal_15
40.353.463,00	Thermal_1	**-33.862,00**	Thermal_16
35.940.581,00	Thermal_2	**-193.635,00**	Thermal_17
32.111.803,00	Thermal_3	**-165.581,00**	Thermal_18
28.762.802,00	Thermal_4	**-266.530,00**	Thermal_19
25.966.727,00	Thermal_5	**-112.051,00**	Thermal_20
23.317.253,00	Thermal_6	**-43.300,00**	Thermal_21
13.407.328,00	Thermal_7	-	Thermal_22
11.923.521,00	Thermal_8	-	Thermal_23

10.490.718,00	Thermal_9	-	Thermal_24

Table 17. Generator's Profitability for the IM

As it can be seen, generators 16 to 21, which are the last dispatched to produce thermal energy, have economic losses. In order to solve this problem, an uplift is going to be applied to Thermal Generator 21 and Thermal Generator 19. The first one is going to be of 19.5 €/MWh and the second one is going to be of 0.9 €/MWh. The first needs to be the biggest one, as the amount of production is smaller, and the losses are shared between fewer hours. Applying these uplifts, the profitability of each generator is presented in Table 18.

Total Profit	Technology	Total Profit	Technology
1.931.852.267,00	PV	10.083.081,00	Thermal_10
3.686.937.511,00	Wind	9.476.947,00	Thermal_11
879.470.865,00	Nuclear	9.299.797,00	Thermal_12
514.352.103,00	Hydro Pump	1.756.203,00	Thermal_13
-	Lithium Batteries	565.089,00	Thermal_14
45.631.812,00	Thermal_0	557.435,00	Thermal_15
40.837.646,00	Thermal_1	**338.740,00**	Thermal_16
36.419.811,00	Thermal_2	**126.286,00**	Thermal_17
32.586.827,00	Thermal_3	**132.081,00**	Thermal_18
29.234.636,00	Thermal_4	**298,00**	Thermal_19
26.436.253,00	Thermal_5	**69.227,00**	Thermal_20
23.784.167,00	Thermal_6	**20,00**	Thermal_21

13.871.899,00	Thermal_7	-	Thermal_22
12.383.723,00	Thermal_8	-	Thermal_23
10.948.148,00	Thermal_9	-	Thermal_24

Table 18. Generator's Profitability with the Uplift for the IM

On the other hand, the renewable energy generators (solar, wind, and hydro pump) and the nuclear generator have the highest profits due to the low production costs compared to the thermal generators and the amount of energy produced during the year.

To finish this section, the comparison between the profit made with the new megawatts developed after the investment will be made against the annuity of each of the technologies. Comparing the two parameters is ideal to understand if the model is optimized and adjusted; being able to slightly cover all the costs of the annuity with the profit made during the year means that there is no room for new megawatts of investment under this conditions. If one extra megawatt was invested for any of the technologies, the total profit per MW would be smaller than the annuity, thus making the project not economically viable for the investors.

Technology	Profit per MW	Annuity
Solar	**36.423 €**	**36.266 €**
Wind	**72.727 €**	**72.532 €**
Hydro Pump	**64.123 €**	**64.106 €**

Table 19. Comparison of Profit per MW & Annuity of the technologies

4.3.Case Comparison

For the final section of this chapter, eight extra cases have been run with modifications of the original parameters modelled for the base case under the investment model. Such parameters, for example, are the investment costs of the lithium batteries, the nuclear installed capacity, an increase in the demand or the need to cover the demand with at least 80% of renewable energy.

Table 20 is going to present a comparison of these cases offering the amount of installed capacity invested per technology in MW and in percentage (compared to the megawatts of existing installed capacity for solar and wind power); the average marginal cost per model, in order to see which model is more expensive; and the amount of the demand covered by renewable energy in each model.

Looking into Table 20, all the modifications mentioned are compared to the base case that was defined in section 4.2. Here are the main cases and the conclusions that can be drawn from them:

- **50% Costs Reduction to Lithium Batteries:** the idea of this case was to try to encourage the investment in lithium batteries. The starting point is the same as in the base case, but the investment cost is reduced by 50%. Despite this measure, the results obtained were the same as in the base case, investing in solar, wind and hydro pump storage.
- **No Hydro Pump:** for the second sensibility analyzed, the hydro pump is erased from the model. Again, the idea is to try to encourage the investment in lithium batteries as a storage system. In this case, the goal is achieved. The total amount of megawatts developed for batteries is of 3.272 MW, fewer than the investment in hydro pump in previous cases. Also, the total use of renewable energy decreased as the investment in solar power went from 33 GW to only 21 GW, despite the increase of investment in wind power. Finally, this sensibility is slightly more expensive as the average marginal cost increased 2,18 €/MWh.
- **No Hydro Pump and 50% Costs Reduction to Lithium Batteries:** this case is the same as the last one, but with the incentive of a 50% reduction in the investment cost for lithium batteries. As it is expected, the investment in lithium batteries increase from 3.272 MW to 5.874 MW, allowing the system to have more storage capacity and thus to be able to consume more renewable energy going from a 57% to a 65% consumption. In this case the investment in solar and wind power changes and the model decides to develop more new solar power. To conclude this case, the average marginal cost increases to 52,43 €/MWh.
- **No Nuclear:** for the fourth sensibility of the model, there is going to be hydro pump and no reduction to the cost of lithium batteries, but the nuclear power is

going to be erased. The idea is to model what could happen in the next years as the nuclear power plants in Spain are planned to disappear by 2030. What can be seen in the results is that the investment in solar and wind power reaches higher heights than the base case. The solar power adds 41.408 MW to the installed capacity and the wind power 29.789 MW, which mean the 209% and 100% respectively. Observing the storage systems, the same happens as in the first sensibilities. The model prefers to invest in hydro pump rather than in batteries because it can store energy more time. Finally, the amount of renewable energy has considerably increased to 76%, reaching almost the goal of 80% targeted by the Government, and the average marginal price is 50,15 €/MWh which is almost the same as in the base case, making this a more affordable sensibility.

- **No Nuclear and 50% Cost Reduction of Lithium Batteries:** again, the idea of this sensibility is trying to encourage the investment in lithium batteries as there has been none in the previous case. From Table 20 it can be inferred that reducing the investment cost, again, does not change the outcome of the model as the results obtained are the same which were gotten in last case.
- **No Nuclear, no Hydro Pump and 50% Cost Reduction of Lithium Batteries:** for this sensibility, it has been decided that, considering that there is not going to be nuclear power, the best conditions for the investment in lithium batteries are in place. Thus, there is not going to be the possibility of investing in hydro pump and the cost of investing in lithium batteries is reduced by 50%. Looking into the results, the installed capacity in the storage system is the second largest of all cases, with a value of 13.582 MW. Compared to the other no nuclear cases, the new solar capacity has decreased by 30% and the wind power has slightly increased reaching the 30.943 MW of investment. The renewable energy consumption has been able to be kept in 75%, almost the same, and the price has increased to an average of 52,70 €/MWh.
- **110% of the Demand and 50% Reduction to Lithium Batteries:** the idea of this sensibility is to analyze what could happen if the demand in Spain increased to 110% of what it currently is. The results obtained are similar to the base case in terms of percentage of renewable energy used and the cost of the system. The difference with it is that, in order to maintain the renewable energy consumed, the

amount of investment in both solar and wind power has increased reaching 40.860 MW for solar power and 27.439 MW for wind power. Regarding the storage systems, again the model prioritizes the investment in hydro pump (9.367 MW), leaving no megawatts for the lithium batteries.

- **80% of Renewable Energy and 50% Reduction to Lithium Batteries:** the objective of the final sensibility is to see how the model responded to the idea of having to have at least an 80% of renewable energy consumed. For that, all the technologies can be used, and the lithium batteries will receive a 50% reduction on their investment cost. The results are very different to the rest of the cases as there are large investments in both storage systems. The lithium batteries have 10.656 MW and the hydro pump 13.967 MW of installed capacity. In this case, the model uses the wind power as its main renewable energy source by investing in it 50.202 MW while only 30.900 MW for solar power. The total amount of renewable energy is 84% and the average marginal cost is 33,47 €/MWh. The issue with this sensibility is that the profit received per MW invested in every technology but the solar is lower than the annuity, making this a non-economically viable case.

Overall, there are some conclusions that can be inferred. The first conclusion is that reducing the investment cost by 50% in the lithium batteries is only worth it when trying to have 80% of the total demand covered by renewable energy. This happens because even though it is cheaper to operate lithium batteries, the hydro pump can store the energy for a longer period of time (4h against 30h). Thus, it is more efficient to invest in hydro pumps if possible. Another insight is that the model always tries to invest in any type of storage system, this aligns with the idea that having more investment in wind and solar power has the necessity of a storage system to contain the curtailments that could occur at some hours.

Finally, the total marginal cost of the different cases does not vary a lot between models, going from a 49,55 €/MWh to a maximum of 52,70 €/MWh except for the model which must have an 80% of renewable energy throughout the whole year and stands with a 33,47 €/MWh which, as it has been mentioned, is not economically viable. It is interesting to see how the percentage of demand covered by renewable can go from minimum of 57% to 84%, depending on the conditions and variations of each model.

	Solar		Wind		Lithium Batteries	Hydro Pump	Average Marginal Cost	% Renewable energy
	MW	%	MW	%	MW	MW	€/MWh	%
Base Case	33.483	169%	21.018	70%	0	8.021	49,55	68%
50% Cost Reduction to Lithium Batteries	33.483	169%	21.018	70%	0	8.021	49,55	68%
No Hydro Pump	21.471	108%	25.942	87%	3.272	0	51,73	57%
No Hydro Pump & 50% Red. to Lithium	24.080	121%	23.394	78%	5.874	0	52,43	65%
No Nuclear	41.408	209%	29.789	100%	0	9.762	50,15	76%
No Nuclear & 50% Red. to Lithium	41.408	209%	29.789	100%	0	9.762	50,15	76%
No Nuclear, no Hydro Pump & 50% Red. to Lithium	35.015	177%	30.943	103%	13.582	0	52,70	75%
110% Demand & 50% Red. to Lithium	40.860	205%	27.439	92%	0	9.367	50,17	68%
80% Renewable & 50% Red. to Lithium	30.900	156%	50.202	168%	10.656	13.967	33,47	84%

Table 20. Case Comparison for the Investment Model

5. Conclusions

The main purpose of this thesis was to understand, define and improve two optimization models that could help to elucidate how the energy and electricity market can evolve thanks to the introduction and investment of new renewable energy technologies.

Reflecting on the initial objectives of the project, three main goals were identified and addressed: the refinement of the previous model, the incorporation of back-up thermal generators and storage technologies, and the optimal allocation of investments in green energy technologies. The first of these objectives was achieved by transforming a model which explored the adjustment of the demand and the offer on daily basis to one that operates on an hourly basis, more accurately reflecting real-life systems. The second goal affects how the thermal energy was considered in the model by employing 25 generators instead of one equivalent and making their price escalate and including start-up and start-off costs. Also, the performance of storage technologies, such as hydro pump and lithium batteries, was formulated and incorporated into the investment model, making the system more reliable and greener in terms of the energy used, as well as being able to reduce the curtailments of solar and wind power. The last objective was to prove and understand how the optimal allocation of these investments was done. This was shown and explained by comparing the total annuity of the investments against the profit made by each megawatt.

Making a comparison between the Economic Dispatch Model and the Investment Model (the base case), several conclusions can be drawn regarding the functioning of the system. First, the amount of renewable energy used without the investment is roughly 40%, which is far from the goals Spain wants to achieve by 2030. Second, by reducing the nuclear energy, if the solar and wind installed capacities are increased, there is no problem of reliability even though there is an important reduction in the base nuclear technology. Third, the addition of storage must be a key target to any system that wants to be based on renewable energy as it provides stability and reduces costs by reducing the amount of back-up technologies that are probably more expensive. Finally, this tool can help to understand the maximum number of megawatts that should be developed to have a healthy investment in terms of covering all the costs, thus preventing an excess that could lead to economic losses that might affect the operation and stability of the system.

Finally, for the investment model, several sensibilities were studied in order to understand the possibilities that this model could offer and how the results could change depending on the different input parameters. From all the cases, the main takeaways where that the model prefers to invest, when possible, in hydro pump because it provides the system with storage capacities as it could hold energy for a larger amount of time. Another key fact that was understood is that there is enough room for new megawatts in the renewable energy technologies, as there has been investments of 20 to 50 GW depending on the technology and case. The last conclusion is that the average marginal cost of the model, if it needs to be economically feasible is around 50 €/MWh.

In summary, the use of the proposed model successfully identified a balance between short-term operational needs and long-term objectives, resulting in a more reliable, sustainable, and cost-effective energy system. The insights acquired will inform future operational and investment strategies. This model provides a deeper understanding of the nuances of electrical energy production and distribution, revealing the intricate reality of the energy landscape.

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Appendix

Appendix I – Alignment with the SDG

The development of an investment model for renewable power resources within a fully decarbonized system is intricately entwined with a spectrum of Environmental, Social, and Governance (ESG) objectives [13].

Aligning with Goals 7 (Affordable and Clean Energy), 13 (Climate Action) and 15 (Life on Land), the project strives to significantly reduce carbon emissions through investments in renewable energy. It also advocates for responsible resource management and the preservation of biodiversity, reflecting a commitment to environmental sustainability.

Socially, the project aligns with Goals 8 (Decent Work and Economic Growth) and Goal 10 (Reduced Inequality), promoting community engagement and stakeholder collaboration, fostering partnerships with local communities affected by renewable energy projects. By generating employment opportunities and improving energy access, the initiative contributes to social well-being and economic development, embodying principles of social equity.

Governance-wise, the project upholds transparent decision-making processes, ensuring that stakeholders are informed and engaged in investment decisions, fulfilling Goal 16 (Peace, Justice and Strong Institutions). By evaluating investments for their environmental and societal impacts, the project embodies responsible investment practices, aligning with ethical and sustainable financial decision-making.

Additionally, it emphasizes regulatory compliance and adherence to environmental standards, reflecting a commitment to legal and regulatory responsibility. In its entirety, this project encapsulates a comprehensive dedication to ESG principles, driving progress toward a more resilient and sustainable energy future.

Appendix II – Code

Economic Dispatch Model

Parameters

```
# Number of Generators
NG_TH = 25 #name updated
NG_PV = 1
NG_W = 1
NG_N = 1

# Number of Loads
ND = 1

# Number of periods
NT = 8760 #time period

t = 1 #Correction factor for daily costs

# Renewable Generators' Costs
C_PV= 5 * t #Cost of PV generation
C_W= 10 * t #Cost of WP generation

# Thermal Generators Cost
C_TH = np.arange(35, 61) * t #Cost of TH generation
C_TH_SU = 20000
C_TH_SD = 20000


# Nuclear Generator's Cost
C_N = 23 * t

# Energy Not Supplied Cost
C_ENS= 7880 * t

# Solar energy capacity
Q_PV = 19785  # Solar PV installed capacity (MW)

# Wind energy capacity
Q_W = 29813     # Wind installed capacity (MW)

# Thermal generator capacity
Q_TH = 1000 #name updated

# Nuclear generator capacity
Q_N = 7000

#Demand max capacity
    Q_D = 30000
```

Model

```
def economic_dispatch_model1(ND, NG_W, NG_PV, NG_TH, NG_N, NT, C_W, C_PV, C_TH, C_N, C_ENS,
QD_norm, QW_norm, QPV_norm, QTH_norm, Q_D, Q_W, Q_PV, Q_TH, on_th, off_th): #Updated
including QT_h_norm and QT, and sorting

    model = gp.Model("ED_model2")
    model.setParam(GRB.Param.MIPGap, 0.001)

    # VARIABLES DEFINITION
     v_w  = model.addMVar(shape=(NG_W, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="v_w")
    v_pv = model.addMVar(shape=(NG_PV, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="v_pv")
    v_th = model.addMVar(shape=(NG_TH, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="v_th") #updated the names of variables, for convention please named the variables
always using lowercase
```

```python
    v_n = model.addMVar(shape=(NG_N, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="v_n")
    #ENS
    v_ens = model.addMVar(shape=(1,NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="v_ens")#updated the shape of matrix variable (NT,1)

    # NEW VARIABLES FOR THERMAL STARTUP AND SHUTDOWN

    c_th_su = model.addMVar(shape=(NG_TH, NT), lb=0, ub=C_TH_SU, vtype=GRB.CONTINUOUS, name="c_th_su")
    c_th_sd = model.addMVar(shape=(NG_TH, NT), lb=0, ub=C_TH_SD, vtype=GRB.CONTINUOUS, name="c_th_sd")
    u_on = model.addMVar(shape=(NG_TH, NT), lb=0, ub=1, vtype=GRB.CONTINUOUS, name="u_on")

    # 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))  #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W

    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)) #v_PV_g, t ≤ Q_PV_h_norm_g, t * Q_PV # updated v_pv[:,t] instead of v_pv[0,t] because with the ":" the constraint is valid for any number of generators otherwise the constrain will consider only 1 generator

    for t in range(NT):
        for g in range(NG_TH):
            model.addConstr(v_th[g, t] <= QTH_norm.iloc[g,t] * Q_TH * u_on[g, t], name="Thermal_Capacity_"+str(g)+"_"+str(t)) #v_th_g, t ≤ Q_TH_h_norm_g, t * Q_TH
            model.addConstr(v_th[g, t] >= 0.1 * QTH_norm.iloc[g,t] * Q_TH * u_on[g, t], name="Thermal_Capacity_Off"+str(g)+"_"+str(t)) #v_th_g, t ≤ Q_TH_h_norm_g, t * Q_TH

    for t in range(NT):
        for g in range(NG_N):
            model.addConstr(v_n[g, t] <= Q_N, name="Nuclear_Capacity_"+str(g)+"_"+str(t))  #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W
            model.addConstr(v_n[g, t] >= 0.9 * Q_N, name="Nuclear_Capacity_Off"+str(g)+"_"+str(t))  #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W

     # Constraints for thermal start-up and shut-down

    for t in range(NT):
        for g in range(NG_TH):
            if t == 0:
                model.addConstr(on_th[g, t] - off_th[g, t] == u_on[g, t], name="Thermal_Operation"+str(g)+"_"+str(t))

            else:
                model.addConstr(on_th[g, t] - off_th[g, t] == u_on[g, t] - u_on[g, t-1], name="Thermal_Operation"+str(g)+"_"+str(t))

    for t in range(NT):
        for g in range(NG_TH):
            model.addConstr(c_th_su[g, t] == C_TH_SU * on_th[g, t], name="Thermal_Startup_Costs"+str(g)+"_"+str(t))
            model.addConstr(c_th_sd[g, t] == C_TH_SD * off_th[g, t], name="Thermal_Shutdown_Costs"+str(g)+"_"+str(t))


     # Power Balance Constraint
    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)) + sum(v_n[g, t] for g in range(NG_N)) + 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[g] * v_th[g, t] + c_th_su[g, t] + c_th_sd[g, t]) for g in range(NG_TH)) + sum(C_N * v_n[g, t] for g in range(NG_N)) + C_ENS * v_ens[:, t]
```

```
for t in range(NT)), GRB.MINIMIZE) #min ∑_t (∑_g (C_PV * v_PV_g, t + C_W * v_W_g, t +
(C_T_a + C_T_b * v_t_g, t + C_T_c * (v_t_g, t) * (v_t_g, t) ) + C_ENS * v_ENS_t)

    model.optimize()


    Obj_value = model.objVal



    #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_n_df = pd.DataFrame(v_n.X, index=list(range(NG_N)), columns=list(range(NT)))
    v_ens_df = pd.DataFrame(v_ens.X, index=["ENS"], columns=list(range(NT)))
          c_th_su_df      =      pd.DataFrame(c_th_su.X,      index=list(range(NG_TH)),
columns=list(range(NT)))
          c_th_sd_df      =      pd.DataFrame(c_th_sd.X,      index=list(range(NG_TH)),
columns=list(range(NT)))
    u_on_df = pd.DataFrame(u_on.X, index=list(range(NG_TH)), columns=list(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 marginal_cost
    marginal_costs_df = pd.DataFrame(marginal_costs)#marginal cost in dataframe format


    return  Obj_value,  v_w_df,  v_pv_df,  v_th_df,  v_n_df,  v_ens_df,  marginal_costs_df,
c_th_su_df, c_th_sd_df, u_on_df
```

Investment Model

Parameters

```
# Number of Generators
NG_TH = 25 #name updated
NG_PV = 1
NG_W = 1
NG_N = 1
#NG = NG_T + NG_PV + NG_W

# Number of Loads
ND = 1

# Number of periods
NT = 8760 #time period

t = 1 #Correction factor for daily costs

# Renewable Generators' Costs
C_PV= 5 * t #Cost of PV generation
C_W= 10 * t #Cost of WP generation

# Thermal Generators Cost
C_TH = np.arange(60, 86) * t #Cost of TH generation
C_TH_SU = 20000
C_TH_SD = 20000


# Hydro pump parameters

capacity1 = 0
efficiency1 = 0.866 #Round trip efficiency 75%
Hr = 1
```

```
P_in_max11 = 0
P_out_max11 = 0
Fixed_batt1 = 1.37
Variable_batt1 = 3
relation1 = 30

# Lithium batteries parameters
capacity2 = 0
efficiency2 = 0.92 #Round trip efficiency 85%
Hr = 1
P_in_max25 = 0
P_out_max25 = 0
Fixed_batt2 = 0.63
Variable_batt2 = 0.00025
relation2 = 4

# Nuclear Generator's Cost
C_N = 23 * t

# Energy Not Supplied Cost
C_ENS= 7880 * t

# Solar energy capacity
Q_PV = 19785  # Solar PV installed capacity (MW)

# Wind energy capacity
Q_W = 29813     # Wind installed capacity (MW)

# Thermal generator capacity
Q_TH = 1000 #name updated

# Nuclear generator capacity
Q_N = 7000 * 0.5


#Demand max capacity
Q_D = 30000
```

Code

```
def economic_dispatch_model1(ND, NG_W, NG_PV, NG_TH, NG_N, NT, C_W, C_PV, C_TH, C_N, C_ENS,
QD_norm,  QW_norm,  QPV_norm,  QTH_norm,  Q_D,  Q_W,  Q_PV,  Q_TH,  capacity1,  capacity2,
efficiency1, efficiency2, P_in_max11, P_out_max11, P_in_max25, P_out_max25, on_th, off_th,
INV_W, INV_PV, INV_11, INV_25, Fixed_batt1, Variable_batt1, Fixed_batt2, Variable_batt2,
relation1, relation2): #Updated including QT_h_norm and QT, and sorting

    model = gp.Model("ED_model2")
    model.setParam(GRB.Param.MIPGap, 0.001)

    # VARIABLES DEFINITION
     v_w  = model.addMVar(shape=(NG_W, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="v_w")
    v_pv = model.addMVar(shape=(NG_PV, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="v_pv")
    v_th = model.addMVar(shape=(NG_TH, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="v_th") #updated the names of variables, for convention please named the variables
always using lowercase
     v_n  = model.addMVar(shape=(NG_N, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="v_n")
    #ENS
     v_ens  =  model.addMVar(shape=(1,NT),  lb=0,  ub=GRB.INFINITY,  vtype=GRB.CONTINUOUS,
name="v_ens")#updated the shape of matrix variable (NT,1)

    # NEW VARIABLES FOR BATTERIES
    inv_25 = model.addVar(lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="inv_25")
    inv_11 = model.addVar(lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="inv_11")
     P_in25 = model.addMVar(shape=(1, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="P_in25")
     P_out25 = model.addMVar(shape=(1, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS,
name="P_out25")
```

```
    SOC_25 = model.addMVar(shape=(1, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="SOC_25")
    P_in11 = model.addMVar(shape=(1, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="P_in11")
    P_out11 = model.addMVar(shape=(1, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="P_out11")
    SOC_11 = model.addMVar(shape=(1, NT), lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="SOC_11")

    # NEW VARIABLES FOR THERMAL STARTUP AND SHUTDOWN

    c_th_su = model.addMVar(shape=(NG_TH, NT), lb=0, ub=C_TH_SU, vtype=GRB.CONTINUOUS, name="c_th_su")
    c_th_sd = model.addMVar(shape=(NG_TH, NT), lb=0, ub=C_TH_SD, vtype=GRB.CONTINUOUS, name="c_th_sd")
    u_on = model.addMVar(shape=(NG_TH, NT), lb=0, ub=1, vtype=GRB.CONTINUOUS, name="u_on")

    # NEW VARIABLES FOR INCREASE OF CAPACITY

    i_w = model.addVar(lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="i_w")
    i_pv = model.addVar(lb=0, ub=GRB.INFINITY, vtype=GRB.CONTINUOUS, name="i_pv")

   # 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 + i_w), name="Wind_Capacity_"+ str(g)+"_"+str(t)) #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W


    for t in range(NT):
        for g in range(NG_PV):
            model.addConstr(v_pv[g, t] <= QPV_norm.iloc[g,t] * (Q_PV + i_pv), name="PV_Capacity_"+str(g)+"_"+str(t)) #v_PV_g, t ≤ Q_PV_h_norm_g, t * Q_PV # updated v_pv[:,t] instead of v_pv[0,t] because with the ":" the constraint is valid for any number of generators otherwise the constrain will consider only 1 generator

    for t in range(NT):
        for g in range(NG_TH):
            model.addConstr(v_th[g, t] <= QTH_norm.iloc[g,t] * Q_TH * u_on[g, t], name="Thermal_Capacity_"+str(g)+"_"+str(t)) #v_th_g, t ≤ Q_TH_h_norm_g, t * Q_TH
            model.addConstr(v_th[g, t] >= 0.1 * QTH_norm.iloc[g,t] * Q_TH * u_on[g, t], name="Thermal_Capacity_Off"+str(g)+"_"+str(t)) #v_th_g, t ≤ Q_TH_h_norm_g, t * Q_TH

    for t in range(NT):
        for g in range(NG_N):
            model.addConstr(v_n[g, t] <= Q_N, name="Nuclear_Capacity_"+ str(g)+"_"+str(t)) #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W
            model.addConstr(v_n[g, t] >= 0.9 * Q_N, name="Nuclear_Capacity_Off"+ str(g)+"_"+str(t)) #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W

   # Constraints to charge the battery 1 when generation exceeds demand
    # CONSTRAINTS DEFINITION
    for t in range(NT):
        model.addConstr(SOC_25[0, t] <= capacity2 + inv_25 * relation2, name="SOC_25_capacity_up"+"_"+str(t)) #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W
        model.addConstr(SOC_25[0, t] >= 0.2*(capacity2 + inv_25 * relation2), name="SOC_25_capacity_low"+"_"+str(t))
        model.addConstr(SOC_11[0, t] <= capacity1 + inv_11 * relation1, name="SOC_11_capacity_up"+"_"+str(t)) #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W
        model.addConstr(SOC_11[0, t] >= 0.2*(capacity1 + inv_11 * relation1), name="SOC_11_capacity_low"+"_"+str(t))
        model.addConstr(P_out25[0, t] <= P_out_max25 + inv_25, name="P_out25_limits"+"_"+str(t)) #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W
        model.addConstr(P_out11[0, t] <= P_out_max11 + inv_11, name="P_out11_limits"+"_"+str(t))
        model.addConstr(P_in25[0, t] <= P_in_max25 + inv_25, name="P_in25_limits"+"_"+str(t)) #v_W_g, t ≤ Q_W_h_norm_g, t * Q_W
        model.addConstr(P_in11[0, t] <= P_in_max11 + inv_11, name="P_in11_limits"+"_"+str(t))


    for t in range(NT):
        if t == 0:
```

```
                model.addConstr(SOC_25[0,  t]  ==  0.2*(capacity2  +  inv_25  *  relation2),
name="SOC_25_constraint_" + str(t))
            model.addConstr(P_out25[0, t] == 0, name="P_out_25_constraint_" + str(t))
        else:
            model.addConstr(SOC_25[0, t] == SOC_25[0, t-1] + ((P_in25[0, t] * efficiency2)
- (P_out25[0, t]/efficiency2)) * Hr, name="SOC_25_constraint_" + str(t))

    # Constraints to charge the battery 2 when generation exceeds demand
    for t in range(NT):
        if t == 0:
                model.addConstr(SOC_11[0,  t]  ==  0.2*(capacity1+  inv_11  *  relation1),
name="SOC_11_constraint_" + str(t))
            model.addConstr(P_out11[0, t] == 0, name="P_out_11_constraint_" + str(t))
        else:
            model.addConstr(SOC_11[0, t] == SOC_11[0, t-1] + ((P_in11[0, t] * efficiency1)
- (P_out11[0, t]/efficiency1)) * Hr, name="SOC_11_constraint_" + str(t))

     # Constraints for thermal start-up and shut-down

    for t in range(NT):
        for g in range(NG_TH):
            if t == 0:
                        model.addConstr(on_th[g,  t]  -  off_th[g,  t]  ==  u_on[g,  t],
name="Thermal_Operation"+str(g)+"_"+str(t))

            else:
                model.addConstr(on_th[g, t] - off_th[g, t] == u_on[g, t] - u_on[g, t-1],
name="Thermal_Operation"+str(g)+"_"+str(t))

    for t in range(NT):
        for g in range(NG_TH):
                      model.addConstr(c_th_su[g,   t]   ==   C_TH_SU   *   on_th[g,   t],
name="Thermal_Startup_Costs"+str(g)+"_"+str(t))
                      model.addConstr(c_th_sd[g,   t]   ==   C_TH_SD   *   off_th[g,   t],
name="Thermal_Shutdown_Costs"+str(g)+"_"+str(t))

    # Constraints for a minimum 80% of renewable energy


#     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)) + P_out11[0, t] + P_out25[0, t] >= 0.8 * sum(QD_norm.iloc[d, t] * Q_D for d
in range(ND)), name="Renewable_limtit" + str(t))


     # Power Balance Constraint
    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))  + sum(v_n[g, t] for g in range(NG_N))
+  v_ens[:,  t]  +  P_out11[0,  t]  -  P_in11[0,  t]  +  P_out25[0,  t]  -  P_in25[0,  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[g] * v_th[g, t] + c_th_su[g, t] + c_th_sd[g, t])
for g in range(NG_TH)) +  sum(C_N * v_n[g, t] for g in range(NG_N)) + INV_PV * i_pv +
INV_W * i_w + INV_25 * inv_25 + INV_11 * inv_11 + Fixed_batt1 * (P_out_max11 + inv_11) +
Variable_batt1 * P_out11[0, t] + Fixed_batt2 * (P_out_max25 + inv_25) + Variable_batt2 *
P_out25[0, t] + C_ENS * v_ens[:, t] for t in range(NT)), GRB.MINIMIZE) #min ∑_t (∑_g (C_PV
* v_PV_g, t + C_W * v_W_g, t + (C_T_a + C_T_b * v_t_g, t + C_T_c * (v_t_g, t) * (v_t_g,
t) ) + C_ENS * v_ENS_t)

    model.optimize()


    Obj_value = model.objVal


    #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_n_df = pd.DataFrame(v_n.X, index=list(range(NG_N)), columns=list(range(NT)))
    v_ens_df = pd.DataFrame(v_ens.X, index=["ENS"], columns=list(range(NT)))
          c_th_su_df       =       pd.DataFrame(c_th_su.X,       index=list(range(NG_TH)),
columns=list(range(NT)))
          c_th_sd_df       =       pd.DataFrame(c_th_sd.X,       index=list(range(NG_TH)),
columns=list(range(NT)))
    u_on_df = pd.DataFrame(u_on.X, index=list(range(NG_TH)), columns=list(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 marginal_cost
    marginal_costs_df = pd.DataFrame(marginal_costs)#marginal cost in dataframe format


    return  Obj_value,  v_w_df,  v_pv_df,  v_th_df,  v_n_df,  v_ens_df,  marginal_costs_df,
P_in11.X,  P_out11.X,  SOC_11.X,  P_in25.X,  P_out25.X,  SOC_25.X,  c_th_su_df,  c_th_sd_df,
u_on_df, i_w.X, i_pv.X, inv_11.X, inv_25.X
```