energies

Article

Optimization of Offshore Wind Power Generation in Response to the 2022 Extreme Drought in Portugal

Fernando M. Camilo [1,2], Paulo J. Santos [1,3,*], Pedro J. Lobato [1] and Sandrina B. Moreira [4,5]

1 ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal; fernando.camilo@estsetubal.ips.pt (F.M.C.); pedro.lobato@estsetubal.ips.pt (P.J.L.)
2 INESC-ID/IST, University of Lisbon, 1000-029 Lisbon, Portugal
3 INESC Coimbra, Department of Electrical and Computer Engineering, University of Coimbra, 3030-290 Coimbra, Portugal
4 ESCE, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal; sandrina.moreira@esce.ips.pt
5 BRU-IUL, Instituto Universitário de Lisboa (ISCTE-IUL), 1649-026 Lisbon, Portugal
* Correspondence: paulo.santos@estsetubal.ips.pt

Abstract: Portugal, in line with the European Union, is aiming for carbon neutrality by 2050 (Net Zero), which implies a transition to sustainable energy sources. Climate change is all too evident, as extreme weather periods are occurring in a cyclical manner with greater brevity to such an extent that the grid operator must deal with production scenarios where it can no longer rely on hydroelectric production given the recurring drought situation. This situation increases dependence on thermal production using natural gas and imports. This has significant economic implications. Portugal has exploited its onshore wind potential, reaching an installed capacity of 5.671 MW by 2022. However, the expansion of onshore wind energy is limited to reinforcing the existing infrastructure. To overcome these challenges, it is necessary to expand the exploitation of the offshore wind potential that is already underway. This article proposes the location of offshore wind production platforms along the Portuguese coast. This allows for an analysis of offshore production and its optimization according to the minimum cost per MWh in the face of extreme scenarios, i.e., in periods of extreme drought where the hydroelectric production capacity is practically non-existent. The model is fed by using market price indications and the amount of energy needed for the following day. Using forecast data, the model adapts offshore wind production for the following day according to the minimization of the average market price. This study presents an optimization model adapted to combat the unpredictability of extreme weather conditions. This strategic framework significantly increases the resilience and reliability of offshore wind energy production, marking a significant advance in the management of renewable energy under the pressure of climate variability. The results of the simulations allow us to conclude that despite the high cost of offshore technology (in deep waters), in extreme climate scenarios, it enables cost reduction and a clear decrease in imports.

Keywords: wind offshore; renewable energy; dynamic model; economic evaluation; optimization methodologies

Citation: Camilo, F.M.; Santos, P.J.; Lobato, P.J.; Moreira, S.B. Optimization of Offshore Wind Power Generation in Response to the 2022 Extreme Drought in Portugal. *Energies* **2023**, *16*, 7542. https://doi.org/10.3390/en16227542

Academic Editor: Eugen Rusu

Received: 15 October 2023
Revised: 6 November 2023
Accepted: 10 November 2023
Published: 12 November 2023

1. Introduction

Around the world, it is essential to accelerate the energy transition towards long-term energy security, price stability and national resilience, with a greater focus on decarbonization, in order to reduce dependence on fossil fuels in electricity consumption [1]. Portugal is making a bold effort to achieve carbon neutrality by 2050 (Net Zero). However, this shift to sustainable energy sources presents significant challenges.

In recent years, Portugal has emerged as a leader in renewable energy adoption, with a notable shift towards wind and solar power contributing to a greener energy matrix. The use of natural gas and renewable energy sources reached 23% of Portugal's total energy supply (TES) in 2018 and 51% of electricity generation in 2018, respectively, as mentioned in [2]. Despite this progress, the nation's energy infrastructure faces significant tests, particularly from extreme climate phenomena like the historic drought of 2022, which exposed vulnerabilities in hydroelectric capacity [3].

Portugal has a high level of renewable energy contribution to electricity consumption, with renewable sources reaching shares of up to 88% in wet years. However, these values heavily rely on a strong component of hydroelectric production [4]. The goal of carbon neutrality by 2050 poses challenges for European countries, with electricity production aiming for approximately 95% renewable energy production [5]. Portugal has a significant hydroelectric power generation capacity. However, climate change is subjecting the Iberian Peninsula, particularly Portugal, to severe and prolonged droughts, which will delay the future utilization of hydro resources for electricity production.

Figure 1 presents a breakdown of the various energy sources contributing to Portugal's energy mix. The graph highlights the proportion of renewable sources, including offshore wind, solar, and hydroelectric power, alongside non-renewable sources, such as fossil fuels. The contrast between the capacity and actual energy production from each source underscores the potential for optimization within the national energy framework.

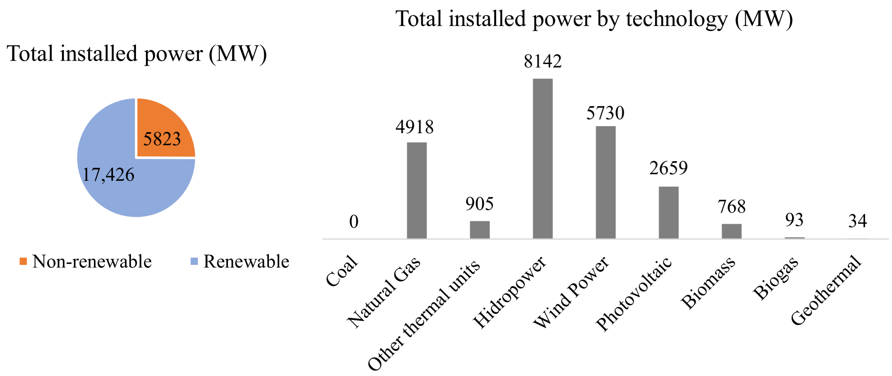

Figure 1. Diversification of energy resources in Portugal.

The decrease in hydroelectric production is evident, as seen in Figure 2, which represents the stored hydroelectric energy in reservoirs [MWh] per week from 2015 to 2022 [6]. Figure 2 clearly depicts the increasingly severe unavailability, with 2022 marking a year of severe drought for Portugal.

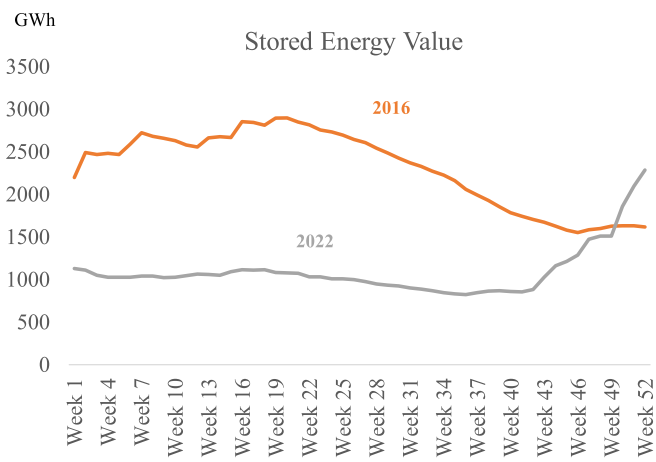

Figure 2. Annual variation in water reservoirs and hydro storage plants in Portugal [6].

Figure 2 delineates the hydroelectric reservoir storage capacity for each year, with distinct lines representing annual data. The blue line corresponds to the maximum levels observed in 2016, a year of high rainfall, while the orange line reflects the minimum levels in 2022, indicative of the extreme drought conditions experienced. The figure provides a stark visual representation of the impact of climatic extremes on hydroelectric power generation and underscores the need for diversifying energy sources, such as offshore wind.

Given that Portugal and Spain share the same energy market, including major rivers, such as the Tejo and Douro, which host the largest power plants in both countries, interdependence becomes crucial. Spain faces a similar situation. Notably, both countries experience a reduction in stored hydroelectric energy [6].

Consequently, there will be a decrease in electricity production from this renewable resource, albeit never reaching zero. Production will continue with run-of-river power plants and pumping stations, with increased reliance on pumping during droughts. Turbines will operate during peak demand hours when this energy is most needed.

Analyzing the contribution of hydroelectric production to final consumption from 2015 to 2022 (Figure 3), a reduced influence of hydro-based energy is observed, particularly in 2022. It is crucial to analyze the contribution of hydroelectric production over this period to observe the decreasing reliance on this technology for consumption satisfaction due to the predicted severe drought scenario.

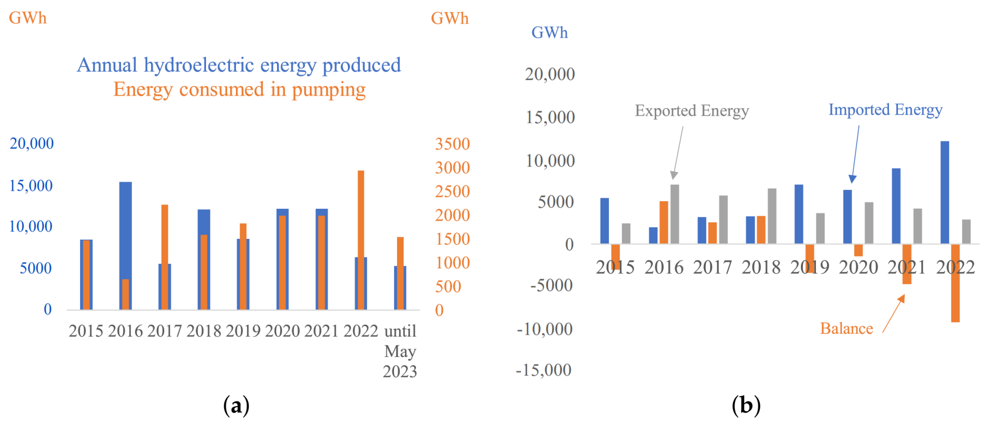

Figure 3. (**a**) Annual hydroelectric energy produced compared with energy consumed in pumping in Portugal from 2015 to May 2023. (**b**) Trade-off between import and export on the Portuguese side.

Comparing energy production in a wet year (2021) to a dry year (2022) (Figure 4) highlights the difference. The portion suppressed in a dry year compared to a wet year amounts to approximately 6.000 GWh in a year (Figure 4).

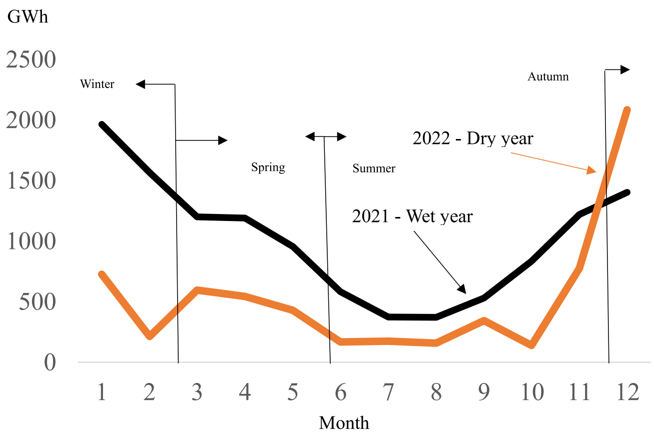

Figure 4. Comparison of hydroelectric power production in two extreme years in Portugal: 2021 (wet year) and 2022 (drought year).

The reduction in hydroelectric production, along with the phasing out of coal-based production, has increased the reliance on energy imports. Analyzing the import trend (Figure 3, above), a clear shift towards a stronger hydroelectric component during dry years is observed.

As referred in [7], a resolute commitment emerges, driven by an unwavering determination to fortify the pursuit of renewable energies while concurrently diminishing the nation's energy reliance, promoting the electrification of the economy and diversification of energy sources through the utilization of endogenous resources.

Portugal's geographic restrictions, wind patterns and environmental limitations make it difficult to utilize onshore wind energy resources, making it imperative to operate offshore wind farms despite associated challenges such as high costs, ecological considerations and labor requirements. The growing offshore wind energy sector in Portugal aligns with the government's ambitious plan to harness up to 10 GW of offshore wind capacity in the near future, targeting 2 GW by 2025 and a more ambitious 10 GW by 2030, as reported in previous studies [8–10]. While these goals may seem ambitious, they are achievable with the effective mitigation of offshore wind energy challenges. This venture not only has the potential to stimulate job creation and boost the economy but also offers an opportunity to reduce Portugal's dependence on imported fossil fuels, paving the way for sustainable energy independence.

The Windfloat Atlantic is currently in operation. Starting such a challenging effort is undeniably ambitious, particularly considering Portugal's current reliance on a single offshore wind farm, Windfloat Atlantic, strategically positioned off the coast of Viana do Castelo [11,12]. Notably set apart by its innovative features, this groundbreaking enterprise stands as the global pioneer of a floating semi-submersible wind farm, showcasing an impressive installed capacity of 25 MW.

Offshore wind energy has significant potential to diversify the energy matrix and reduce greenhouse gas emissions (GGEs). Portugal has comfortable maritime conditions, which makes the country an attractive place for the installation of these parks. However, the economic viability of these ventures is a crucial factor to be considered. Several studies, as stated below, have had the economic viability of offshore wind farms, providing valuable insights for decision makers, investors, and professionals in the energy sector.

The process of calculating costs typically involves the anticipation of two distinct cost categories, contingent upon the park's distance from the coast and the depth of the water under consideration. These categories encompass investment costs and operation and maintenance costs as referred in [13]. Reference [14] evaluates the potential economic value of investing in offshore wind farms in the north of Portugal, Viana do Castelo. Economic results indicate the viability of offshore wind energy in this location. Floating platforms will play a vital role in achieving Net Zero goals for many countries, as they allow access to wind resources in deeper waters where fixed offshore turbines are impractical but are still in the early stages of development with various design options. A review about the evolution of floating offshore wind platforms is discussed in [15]. Reference [16] presents a method to determine the economic feasibility of floating offshore wind farms at the Portugal continental coast. The findings identify the ideal floating offshore wind platform based on economic parameters and identify the most suitable area within the study region to implement a floating offshore wind platform. This study concludes that individual risk exposure must be considered, historical records may not predict future risk, and probabilistic methods are crucial for accurate financial valuation in offshore wind projects, while economic cycles and investor judgment must also be considered.

Some economic evaluation methodologies for renewable energy projects are presented in [17]. In addition, the authors of this research propose a new framework to facilitate economic analysis, assisting decision makers in selecting the most appropriate methodology for investments before moving forward. An interesting review of the methods for the financial evaluation of renewable energy projects is presented in paper [18]. The two main objectives of this article are, firstly, to revise publications on the financial evaluation of renewable energy projects between the years 2011 and 2020 and, secondly, to provide a critical analysis of the literature under review. The main findings of this paper indicate that while traditional methods remain prevalent for evaluating the financial aspects of renewable energy projects, the significance of the levelized cost of energy (LCOE) and real option approaches has been increasing to address the intricate aspects and comparisons of these projects. Reference [19] presents a study of a risk model for evaluating offshore wind projects, using operational and macroeconomic data to analyze the project-specific risk premium, represented as stochastic variables, and conducting a probabilistic financial analysis through Monte Carlo Simulation. Another interesting review on life cycle cost modeling and the economic analysis of wind energy is addressed in [20]. This review provides a macro-level explanation of the entire life-cycle composition, economic analysis method and cost modeling process of wind energy, as well as summarizing the differences in cost composition and modeling between various types of wind farms and the applicability of different economic analysis methods and valuation indicators. The authors offer suggestions to achieve the precise and dependable economic evaluation of wind power in diverse regions and environments, providing valuable references to enhance the economic efficiency of wind farms.

The advent of offshore wind energy in Portugal presents a unique set of challenges, driven mainly by the deep offshore geography that precludes the use of fixed-bottom turbines. Instead, floating platforms become the necessary alternative, despite their higher cost implications when compared to their shallower water counterparts. On the other hand, it is important that there is a strategy of expansion and technological innovation to mitigate these costs and reinforce the economic viability of offshore wind energy in Portugal's renewable energy portfolio. In Reference [10], the authors address a strategy more attuned to Portugal's socioeconomic context, exploring the resulting opportunities and the challenges. They also dissect the critical issues that must be tackled to successfully navigate this pathway.

In the wake of a severe drought in 2022, Portugal's energy sector grappled with a hydroelectric production crisis, compounded by diminished outputs from both hydroelectric and onshore wind sources. This paper proposes an optimization analysis of offshore wind production in a scenario where the production system faced a hydroelectric production crisis during an extreme drought, in the year 2022. Both hydroelectric and onshore wind production were very low. The solution involved resorting to importation and thermal production based on natural gas as the only means to compensate for this production deficit. One of the constraints is the limit on instantaneous power that can be imported, which, in the case under study, is set at 5.000 MW, according to the regulator. The utilization of this available power can, in certain situations, jeopardize the system's integrity. The advent of extreme weather conditions presents unprecedented challenges to renewable energy systems. Confronting these challenges, our research advances an innovative optimization model tailored to navigate these complexities. This model capitalizes on the complex interplay between meteorological data and offshore wind energy generation, striving for a balance between system dependability and energy self-sufficiency.

Among the vulnerabilities of hydroelectric energy, our study positions offshore wind energy as an axis of Portugal's renewable strategy [21], taking advantage of climate forecasting to predict and stabilize wind energy production. As supported by Reference [22], the diversification of forecasting models is paramount in enhancing the robustness of wind energy.

This paper also delineates Portugal's energy composition, underscoring the essential role of offshore wind in the nation's energy portfolio and its ability to withstand climate volatility—a sentiment reiterated by Reference [23]—which underscores the resilience of Portugal's carbon-neutral power objectives in the face of climatic changes.

Finally, this article analyzes the impact of this type of resource on the spot market price. A methodology for optimization is developed to minimize the spot market price, as the introduction of offshore wind production implies an increase in the cost per MWh due to the high cost of deep-sea exploitation, which is typically priced in [EUR/MWh]. Although applied to a specific case study, the findings can be generalized to other regions or case studies.

This article is organized as follows: Section 2 shows the methodology, starting by characterizing the wind resource and developing the models that support the case study. Section 3 presents the simulation results and discusses their implications. Finally, Section 4 presents the conclusions.

2. Methodology Applied to the Case Study

Electricity consumption in Portugal remained stable between 2015 and May 2023 as indicated in Figure 5. In mainland Portugal, all coal-based power production units were deactivated, ceasing operations in 2020. This led to an increased need for energy imports as depicted in Figure 5. Simultaneously, there was a decrease in hydroelectric production due to the drought conditions that Portugal has been experiencing, particularly in the year 2022.

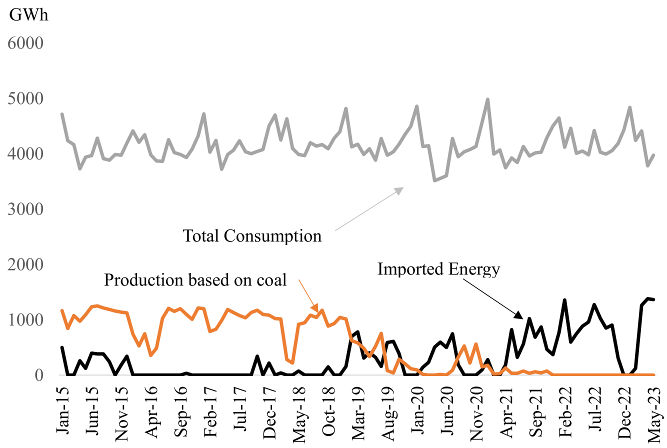

Figure 5. Changes in imported energy due to the reduction in coal-based production.

It is necessary to further analyze the low hydroelectric production recorded due to the situation of extreme drought, where reliance on hydroelectric production is decreasing. The hydroelectric production and coal-based production in 2018 amounted to 10.552 GWh. This energy quantity was subtracted from the system. Energy imports during the year 2022 reached 9.661 GWh. Traditionally, Portugal did not import such a significant amount of energy. In this study, we assume that this energy will need to be replenished in the system by being sourced from wind power platforms. There is no direct substitution, especially considering the increased energy production from photovoltaic units and other types of renewable units.

Investment in photovoltaics has been significant, and it is expected to grow substantially. The total installed capacity is projected to reach approximately 1.332 MW by the year 2023 [5]. However, it is in the off-shore potential that the capacity to expand renewable production resides since it is available on a continuous basis, although it has intermittency issues, which can be somewhat mitigated by increasing the installed capacity.

2.1. Assessment of Offshore Wind Potential

Portugal has a high offshore wind potential and is one of the European countries with the largest continental shelf. Although it is very extensive, the continental shelf is narrow. This apparent disadvantage, with its waters being deep at relatively short distances from the coast, motivated the search for offshore technological solutions different from those used in Northern Europe. Portugal was thus, out of necessity, a pioneer in operating wind turbines mounted on floating platforms and already operates a floating offshore wind farm consisting of three platforms off the coast of Viana do Castelo, with a total installed capacity of 25 MW, and the distance from the coast is about 20 km. The power in question and the distance from the coast allow for the establishment of the High Voltage Alternated Current (HVAC) connection [11].

The three most advantageous areas in terms of wind potential are located in the north, center, and south of the country. These regions include Viana do Castelo, off the coast of Lisbon, and in the southern zone, Sagres (Figure 6A,B).

The wind models used as the basis for this article were created using the WindAtlas database [24]. This database is recognized in the scientific community and allows for data collection with an acceptable level of accuracy considering the analyses to be conducted. With these data, it was possible to determine the average wind speed (Figure 6C).

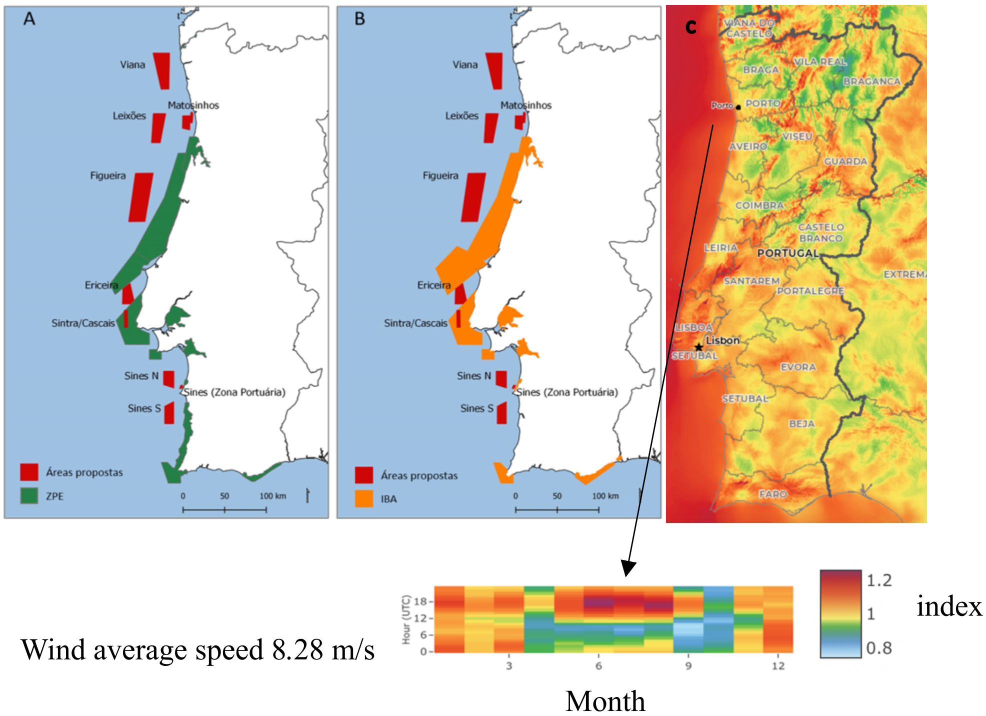

Figure 6. (**A**) Location of the proposed areas ("áreas propostas") for development of offshore wind farms in relation to the marine and coastal special protection zones (ZPE); (**B**) Important Bird and Biodiversity Areas (IBA). (**C**) Construction of wind models for most favorable zones with an average speed of 8.28 m/s in Viana do Castelo.

The wind energy production on floating platforms in a marine environment has significant impacts on biodiversity, especially on birds [25]. The selected areas safeguard the special protection zones that limit the placement of wind farms along the coast in order to minimize the impact that these new wind infrastructure may have on bird life, especially on the migratory routes of seabirds (Figure 6A,B).

Respecting these environmental restrictions, data were collected in three of these coastal areas of mainland Portugal (off Viana do Castelo, Figueira da Foz and Sines) for the possible future locations of offshore parks (Figure 6). It was possible to determine the average annual wind speed for a height of 100 m for each of the selected zones. WindAtlas [24] allows the visualization of the evolution of the average annual wind speed, allowing the construction of average wind models with hourly resolution.

Although floating offshore wind farms use turbine technology similar to onshore wind farms, offshore installations have the advantage of being able to exploit more constant and higher wind speeds, and with fewer restrictions on the area they occupy and the distance from the rotor to the water surface when compared to the onshore case. As a result, the areas of offshore farms and the dimensions of wind turbines can be larger, leading to generally better performance indicators for these farms. In Portugal, the offshore wind resource is generally characterized by average wind speeds, at 100 m height, of the order of 8 m/s. However, the average wind speed is not constant over the years; therefore, there is a randomness that must be taken into account when building wind models. With these premises in mind, wind models were built for all selected regions that allow, with an hourly resolution, to estimate the average wind speed that supports the wind turbine models to be used. These wind models allow us to determine the average wind profile for each of the selected marine regions. Therefore, it was decided to continue the use of turbines with a unitary power of 8 MW [26]. In this study, the authors consider nine turbines distributed across three parks, strategically located in areas with lower environmental impact.

Figure 7 displays the characteristics of the wind turbine selected for this research. This figure displays the typical power curve for a wind turbine, depicting how the power output in kilowatts (kW) and the coefficient of performance (C_p) vary with wind speed. The curve shows a progressive increase in power output with rising wind speeds until reaching the turbine's rated speed, at which point the output stabilizes and remains constant, reflecting the operational limit designed to prevent turbine damage under high-wind conditions.

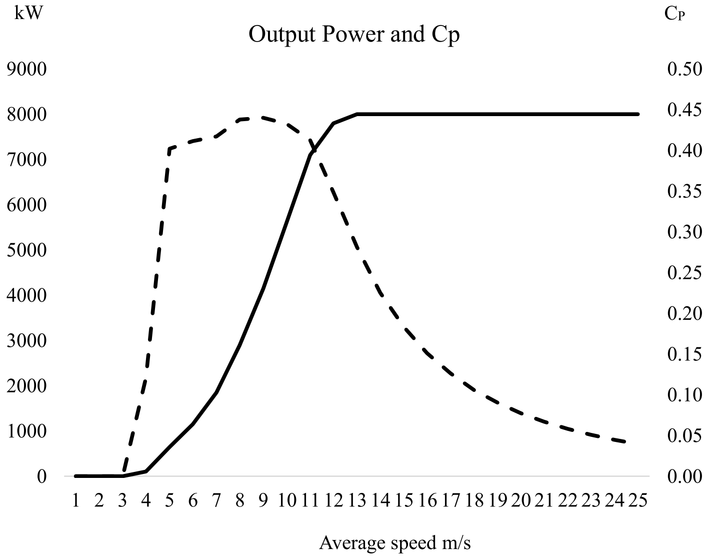

Figure 7. Power output and performance coefficient (C_p) of the wind turbine as a function of wind speed.

The costs used in this work was given by the network operator considering an average basis. The capital and maintenance cost of wind turbines, although important for a detailed technical-economic assessment, are outside the scope of this analysis and will be addressed in a future work.

Two cases of turbine operation were considered to have favorable and less-favorable wind speed profiles. These profiles were determined based on the average daily profiles of maximum and minimum wind speeds for the month in question (February). For both cases, we estimated the average daily production per turbine. It is possible to predict an average daily energy production per turbine, which on average can vary between 62 and 106 GWh.

2.2. Methodology for Optimizing Energy Source Combinations

The suggested algorithm aims to perform optimization to determine the optimal combination of a mix of energy sources, considering availability constraints and cost minimization. This methodology is represented through a basic flowchart displayed in Figure 8.

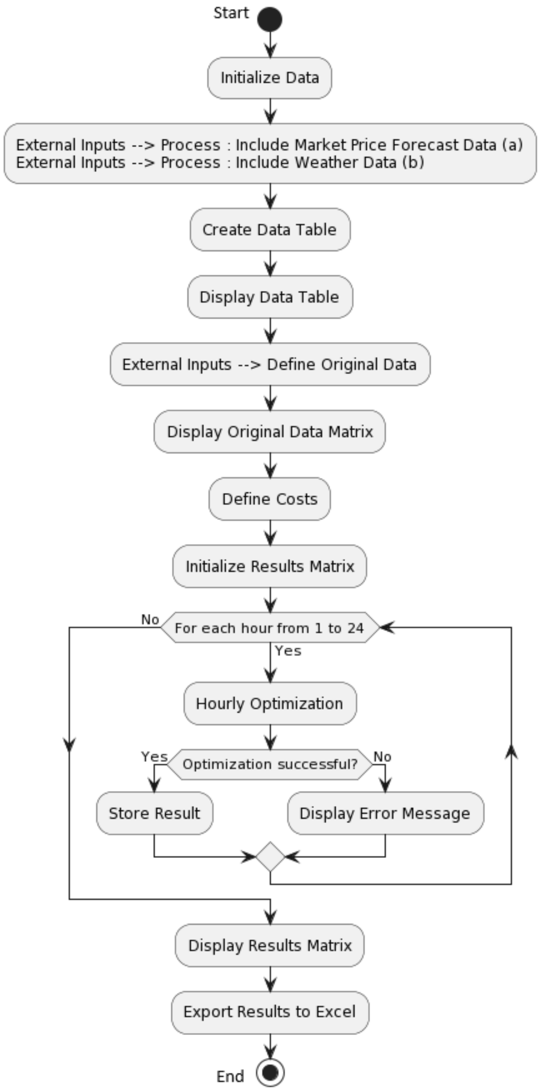

Figure 8. Basic flowchart of the implemented methodology.

The methodology is explained as follows:

- Mathematical Formulation: The optimization problem is formulated as a linear programming issue, aiming to minimize the total cost of energy generation. The objective function and constraints are mathematically described as follows:

$$\text{minimize} \quad C = \sum_{i=1}^{n} c_i \cdot x_i \tag{1}$$

$$\text{subject to} \quad a_i \leq x_i \leq b_i, \quad \forall i \in \{1, \ldots, n\} \tag{2}$$

$$\sum_{i=1}^{n} x_i = D \tag{3}$$

$$x_i \geq 0, \quad \forall i \in \{1, \ldots, n\} \tag{4}$$

where:

- C is the total cost.
- c_i is the unit cost of generation for technology i.
- x_i is the amount of energy produced by technology i.
- a_i and b_i are the lower and upper bounds for energy generation by technology i, respectively.

- D is the total energy demand to be met.
- n is the number of energy generation technologies considered.

- Details on Cost Vectors and Constraints: The costs associated with each energy generation technology (c_i) and the availability constraints (a_i and b_i) are derived from a combination of historical data, market forecasts, and meteorological models. The flowchart, displayed in Figure 8, describes the process of how these data are transformed into parameters for the optimization model.
- Input Data: The availability data for various power generation technologies, in MW, are available, as well as the costs associated with each technology, in [EUR/MWh] [27]. In the flowchart, two external inputs are presented: (a) market price forecast data with a 24 h lead time, and (b) the possibility of weather data for wind or offshore wind power forecast. The objective is to determine the amount of energy to be produced by each technology to meet a specific demand.
- Formulation of the Optimization Problem: The problem is formulated as linear programming, where the objective is to minimize the total cost of energy generation subject to availability constraints and equality of demand. The cost vector and constraints are defined according to the input data.
- Call to `linprog`: The algorithm uses MATLAB's `linprog` function to solve the optimization problem. Linprog is a linear optimization function that finds the optimal values of the decision variables (amounts of energy to be produced by each technology) that minimize the objective function (total cost) subject to linear constraints. The authors choose the `linprog` function of MATLAB [28], among others, to implement in the algorithm due to its efficiency, ease of use, and flexibility to solve linear optimization problems, specifically to determine optimal power generation based on cost and availability constraints.
- Justification for the Choice of `linprog`: The MATLAB `linprog` function is used due to its proven computational efficiency and flexibility in solving linear optimization problems. The choice of this function is justified by the linear nature of the problem and the need to find an optimal solution within a reasonable computational time frame.
- Convergence Verification: After running `linprog`, we verify the convergence of the solution using standard optimization criteria. We discuss the tolerance parameters and other settings used to ensure that the found solution is stable and reliable.
- Optimization Results: These include both the amounts of energy produced by each technology and the minimum total cost, and are displayed as output. Optimization results were validated against historical scenarios and compared with outcomes obtained from other models to ensure accuracy and applicability. This validation helps to confirm the robustness of the proposed methodology.
- Comparison of `linprog` with Other Optimization Methods: The authors choose MATLAB's `linprog` for several strategic reasons. Firstly, its computational efficiency is well established, particularly for large-scale linear problems, which is crucial in our context of real-time optimization. Moreover, the ease of use and integration with the MATLAB environment allows for more fluid modeling and data analysis, significantly accelerating development.

While other tools such as `CPLEX` [29] and `Gurobi` [30] are equally powerful, their flexibility for rapid parameter changes is less convenient for our use case. Additionally, the robustness of `linprog` in handling the dynamic nature of energy optimization problems is a deciding factor, given the frequent updating of input data.

Although there are open-source alternatives, the authors choose `linprog` due to the commercial support and the vast user community it offers, thus ensuring a reliable and well-supported solution for our optimization analysis.

To ensure the fundamental integrity of our optimization model, the authors meticulously source their data from respected organizations such as the National Energy Networks (REN) [4], the Portuguese Renewable Energy Association (APREN) [5], the ENTSO-E [6] and the Global Wind Atlas [24]. These sources are known for their rigorous data reliability standards. They are instrumental not only for initial data acquisition, but also as references for cross-referencing and validating our datasets. Furthermore, by comparing historical trends and aligning with peer-reviewed predictive models from these authorities, the authors strengthen the accuracy of their input data, thereby increasing the robustness and credibility of our model results. In conclusion, given the high costs associated with offshore wind technology (€/MWh), our model seeks to optimize the combination of energy sources to minimize costs in the 24 h spot market. This methodology is intended for use by network operators during the initial formation of the spot market on the preceding day, incorporating predictive climatic data for the following day. By simulating scenarios 24 h in advance, our approach aims to reduce reliance on natural gas or other thermal energy production, thus providing a strategic tool for enhancing resilience and cost efficiency in renewable energy sourcing.

3. Model Simulations—Main Results and Discussion

Multiple scenarios were simulated, and in this section, we will present only the most significant data. Thus, nine turbines were placed, divided into three parks in suitable locations according to the zones of lower environmental impact as previously referenced in Section 2.1.

The scenarios of extreme and severe drought are becoming increasingly recurrent, prompting the use of the thermal component, particularly natural gas. As a non-producing country, Portugal is subject to the natural gas prices in international markets.

The introduction of offshore wind power (in deep waters) yields positive results. As displayed in Figure 9, the introduction of offshore production leads to a reduction in the average energy price, in the spot market situation. Thus, despite the high unit cost of this technology, in a situation of severe drought where hydropower production is minimal, this is a viable solution.

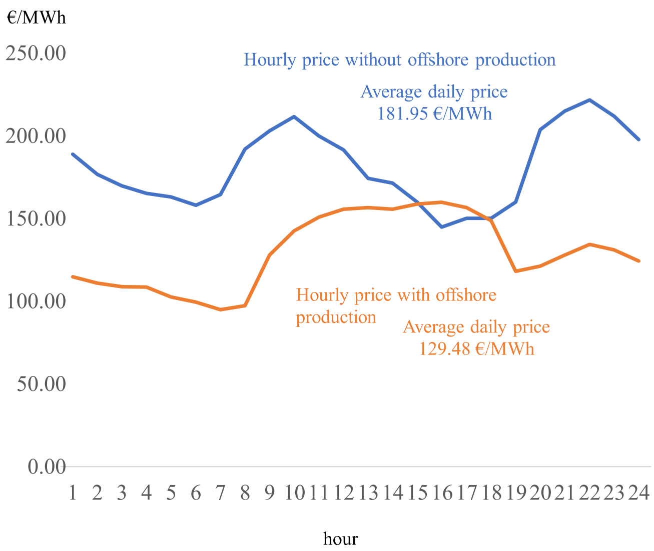

Figure 9. Simulation results.

The results of the developed methodology enable the placement and management of offshore wind energy in order to minimize costs throughout the forecast period. Another crucial aspect is that the reduction is greater with increasing installed capacity to minimize the price (see Figure 10).

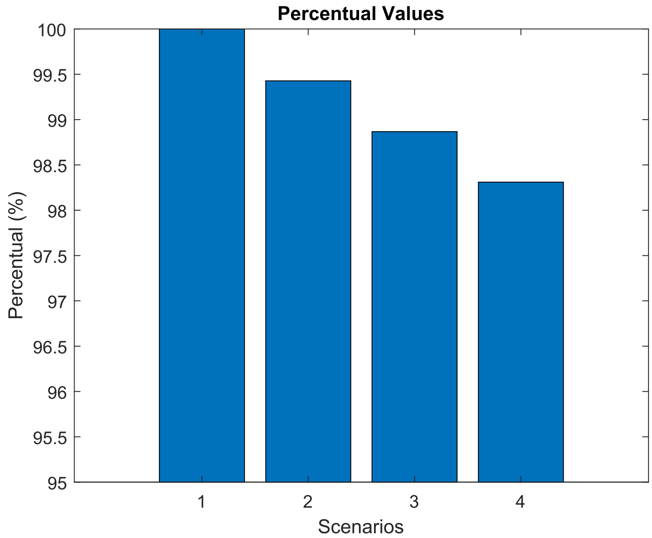

Figure 10. Comparative Analysis of Energy Production by scenario.

Figure 10 presents four scenarios. The horizontal axis categorizes the different scenarios assessed, reflecting variations in energy production strategies under diverse conditions. The vertical axis quantifies the resulting energy production in each scenario, offering a visual representation of their comparative performance. Bar 1 is the base-case scenario, without offshore wind energy. Bars 2 to 4 illustrate three distinct wind parks, each characterized by a varying number of turbines. Bar 4 features nine turbines, representing the maximum threshold considered for our analytical study.

According to what was demonstrated throughout the study, despite the high price of the technology, this type of production (off-shore on deep waters) proves to be an alternative when the electrical energy system is subject to extreme dry weather conditions. Portugal under normal conditions can satisfy consumption only with the water and wind components. Energy production in wet years reaches around 40% of daily energy consumption. However, with the worsening of drought scenarios, the water component is practically reduced to values around 10%, thanks to the contribution of units that have pumping. In this way, it was possible to optimize the amount of offshore wind production in order to overcome this production deficit without increasing the average price of daily energy. The intermittency of this resource can be overcome depending on a minimum number of wind turbines that can ensure a minimum production; in the case study, they are nine in number. For a wet scenario the contribution of this type of production, i.e., production surpluses can be used in storage situations in places where the network is under more pressure, that is, at interconnection points with the European network, as well as being used in pumping.

The proposed model constitutes a strategic tool to increase the resilience and efficiency of wind energy generation in the face of climate change. It also provides practical information for energy policy and infrastructure planning, leveraging the latest climate forecasting and renewable energy technologies. This method distinguishes itself by proactively anticipating climate-induced challenges, facilitating more resilient infrastructure planning and energy policy formulation. It does so by effectively bridging the gap between the unpredictable dynamics of weather and the consistent demand for energy, thereby setting a new standard for integrating environmental factors into energy management strategies.

4. Conclusions

The decarbonization of the electrical energy production sector poses challenges to operators of electrical energy systems. In the present case study, we are faced with a situation in which initially the accommodation of the extinction of coal-based production only represents 8.3% of the total installed power, a value that in itself does not represent a major problem. However, in this case study, the installed power from non-renewable sources reaches around 35%.

In the case study, two scenarios are presented: one of severe drought in which hydropower-based production was minimal, in contrast to a scenario where hydropower-based energy production was abundant. In a scenario with ample rainfall, there is no need to resort to thermal production. However, profound climate changes bring about scenarios of extreme drought. The hydropower component in this case represents a reduction in the availability of installed capacity by 31%. In this situation, reliance on energy imports is higher, which poses challenges to the operator since the available power is pre-agreed and depends on the connection point. For this case study, the value of this limitation was 5.000 MW in terms of instantaneous power.

In parallel with the extreme drought scenario, in this case, there was a decrease in onshore wind production, which resulted in greater stress on the system. Offshore wind production presents itself as the only viable alternative to solve this problem. The greatest amount of energy is consumed at nighttime, and therefore, peak demand normally occurs at this period, which makes the scenario challenging.

Despite the high costs of offshore technology [EUR/MWh], this type of technology is the only solution in adverse scenarios. As demonstrated in this article through optimization algorithms, positioning this type of production in order to minimize the daily average cost of energy in the spot market is essential.

Due to the more consistent wind patterns, electricity production based on offshore technology exhibits regularity and lower intermittency when compared to onshore production. In scenarios of severe drought, it represents an important source of production, allowing costs to be minimized by relieving production based on natural gas and energy imports. In scenarios with lower demands on the production system, it acts as an energy source that can be used in storage to reinforce the electrical energy network. Even during non-peak periods, it is a valuable aid for hydroelectric power plants with the possibility of pumping, and acts in a complementary way with photovoltaic-based production.

This research emphasizes the significance of offshore wind technology in addressing the challenges related to decarbonization in the electricity sector. However, the authors acknowledge that this study has limitations and suggest that further analysis is needed to evaluate the high costs associated with offshore technologies. This evaluation aims to determine their profitability in the medium and long term. Consequently, in future research, the authors aim to carry out a more in-depth economic evaluation to identify strategies for mitigating the costs associated with offshore technology, contributing, in this way, to its integration into the electrical energy system.

Author Contributions: Conceptualization, F.M.C. and P.J.S.; methodology, F.M.C. and P.J.S.; software, F.M.C.; validation, F.M.C., P.J.S., P.J.L. and S.B.M.; formal analysis, F.M.C., P.J.S., P.J.L. and S.B.M.; investigation, F.M.C., P.J.S., P.J.L. and S.B.M. data curation, F.M.C. and P.J.S.; writing—original draft preparation, F.M.C., P.J.S., P.J.L. and S.B.M. writing—review and editing, visualization, F.M.C., P.J.S., P.J.L. and S.B.M. supervision, F.M.C., P.J.S., P.J.L. and S.B.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Instituto Politécnico de Setúbal and the Portuguese Foundation for Science and Technology under project grants UIDB/00308/2020.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

APREN	Portuguese Renewable Energy Association
ENTSO-E	European Network of Transmission System Operators for Electricity
GGE	Greenhouse Gas Emissions
HVAC	High Voltage Alternated Current
IBA	Important Bird and Biodiversity Areas
LCOE	Levelized Cost of Energy
REN	National Energy Networks
TES	Total Energy Supply
ZPE	Special Protection Zones

References

1. World Energy Transitions Outlook. 2022. Available online: https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2022 (accessed on 22 July 2023).
2. OECD iLibarary. Portugal. In *OECD Inventory of Support Measures for Fossil Fuels: Country Notes*; OECD Publishing, Ed.; OECD eBooks: Paris, France, 2023. [CrossRef]
3. Sowah, J.K., Jr.; Genc, S.Y.; Castanho, R.A.; Couto, G.; Altuntas, M.; Kirikkaleli, D. The Asymmetric and Symmetric Effect of Energy Productivity on Environmental Quality in the Era of Industry 4.0: Empirical Evidence from Portugal. *Sustainability* **2023**, *15*, 4096. [CrossRef]
4. Electricity—Monthly Balance. Available online: https://datahub.ren.pt/en/electricity/monthly-balance/?date=2023-01-31 (accessed on 6 July 2023).
5. APREN. *Eletricidade Renovável No Sistema Elétrico Português até 2050*; APREN—Associação Das Energias Renováveis: Lisboa, Portugal, 2018. Available online: https://www.apren.pt/contents/documents/apren-2050-pt.pdf (accessed on 6 July 2023).
6. ENTSO-E Transparency Platform. Available online: https://transparency.entsoe.eu/dashboard/show (accessed on 6 July 2023).
7. República Portuguesa. *Plano Nacional Energia e Clima 2030 Aprovado Em Conselho de Ministros*; República Portuguesa—Gabinete do Ministro e da Ação Climática: Lisboa, Portugal, 2020. Available online: https://www.portugal.gov.pt/download-ficheiros/ficheiro.aspx?v=%3D%3DBAAAAB%2BLCAAAAAAABACztDQyAgDZs3qiBAAAAA%3D%3D (accessed on 20 July 2023).
8. Case Study: How Is Portugal Preparing to Accelerate Offshore Wind Energy Production? Available online: https://www.lisbonenergysummit.com/media-centre/industry-news/2023/may/how-is-portugal-preparing-to-accelerate-offshore-wind-energy-production/ (accessed on 20 July 2023).
9. Galp and Total Energies Look at Offshore Wind Opportunities in Portugal. Available online: https://ocean-energyresources.com/2023/06/21/galp-and-totalenergies-look-at-offshore-wind-opportunities-in-portugal/ (accessed on 20 July 2023).
10. Vieira, M.; Henriques, E.; Amaral, M.; Arantes-Oliveira, N.; Reis, L. Path discussion for offshore wind in Portugal up to 2030. *Mar. Policy* **2019**, *100*, 122–131. [CrossRef]
11. Windfloat Atlantic. Offshore Wind Energy. Available online: Https://www.windfloat-atlantic.com/pt-pt/ (accessed on 20 July 2023).
12. Duarte, T.; Peiffer, A.; Pinheiro, J.M. WindFloat Atlantic Project: Technology Development Towards Commercial Wind Farms. In Proceedings of the Annual Offshore Technology Conference, Houston, TX, USA, 2–5 May 2022. [CrossRef]
13. Ferreira, P.; Vieira, F. Evaluation of an Offshore Wind Power Project: Economic, Strategic and Environmental Value. *World Acad. Sci. Eng. Technol.* **2010**, *4*, 2132–2137.
14. Lopes, A.F. The Economic Potential Value of Offshore Wind in the North of Portugal. In Proceedings of the 13th International Conference on the European Energy Market (EEM), Porto, Portugal, 6–9 June 2016; IEEE: Piscataway, NY, USA, 2016; pp. 1–6. [CrossRef]
15. Edwards, E.C.; Holcombe, A.; Brown, S.; Ransley, E.; Hann, M.; Greaves, D. Evolution of Floating Offshore Wind Platforms: A Review of at-Sea Devices. *Renew. Sustain. Energy Rev.* **2023**, *183*, 113416. [CrossRef]
16. Castro-Santos, L.; Silva, D.; Bento, A.R.; Salvação, N.; Guedes Soares, C. Economic Feasibility of Floating Offshore Wind Farms in Portugal. *Ocean Eng.* **2020**, *207*, 107393. [CrossRef]
17. Dranka, G.G.; Cunha, J.; de Lima, J.D.; Ferreira, P. Economic Evaluation Methodologies for Renewable Energy Projects. *AIMS Energy* **2021**, *8*, 339–364. [CrossRef]
18. Delapedra-Silva, V.; Ferreira, P.; Cunha, J.; Kimura, H. Methods for Financial Assessment of Renewable Energy Projects: A Review. *Processes* **2022**, *10*, 184. [CrossRef]
19. Yeter, B.; Garbatov, Y.; Brennan, F.; Kolios, A. Macroeconomic Impact on the Risk Management of Offshore Wind Farms. *Ocean Eng.* **2023**, *284*, 115224. [CrossRef]
20. Liu, J.; Song, D.; Li, Q.; Yang, J.; Hu, Y.; Fang, F.; Hoon Joo, Y. Life Cycle Cost Modelling and Economic Analysis of Wind Power: A State of Art Review. *Energy Convers. Manag.* **2023**, *277*, 116628. [CrossRef]
21. Wang, J.; Wei, X.; Juanatas, R. Study on the optimization strategy of offshore wind power. *Int. J. Low-Carbon Technol.* **2023**, *18*, 367–372. [CrossRef]

22. Prasad, S.R.; Naik, M.G. A Review on Wind Power Forecasting Models for improved Renewable Energy Integration. In Proceedings of the International Conference on Information Science and Technology Innovation, ICoSTEC, Yogyakarta, Indonesia, 26 February 2022; pp. 113–118. [CrossRef]
23. Fortes, P.; Simoes, S.G.; Amorim, F.; Siggini, G.; Sessa, V.; Saint-Drenan, Y.-M.; Carvalho, S.; Mujtaba, B.; Diogo, P.; Assoumou, E. How sensitive is a carbon-neutral power sector to climate change? The interplay between hydro, solar and wind for Portugal. *Energy* **2022**, *239*, 122106. [CrossRef]
24. Global Wind Atlas. Available online: https://globalwindatlas.info/en (accessed on 30 May 2023).
25. News—Centre for Ecology, Evolution and Environmental Changes (ce3c). Available online: https://ce3c.ciencias.ulisboa.pt/outreach/press&events/ver.php?id=1497 (accessed on 11 July 2023).
26. Wind-Turbine-Models. Available online: https://en.wind-turbine-models.com/turbines/318-vestas-v164-8.0 (accessed on 13 August 2023).
27. Remuneration of Renewable Energies. Available online: https://www.dgeg.gov.pt/pt/areas-setoriais/energia/energia-eletrica/producao-de-energia-eletrica/producao-potencia-instalada-superior-a-1-mva/remuneracao-das-energias-renovaveis/ (accessed on 25 August 2023).
28. Mathworks. Available online: https://www.mathworks.com/products/matlab.html (accessed on 13 May 2023).
29. Bliek, C.; Bonami, A.; Lodi, A. Solving mixed-integer quadratic programming problems with IBM-CPLEX: A progress report. In Proceedings of the Twenty-Sixth RAMP Symposium, Hosei University, Tokyo, Japan, 16–17 October 2014; pp. 16–17. Available online: https://plato.asu.edu/APM523/cpl_miqp.pdf (accessed on 3 November 2023).
30. Gurobi Optimizer—The World's Fastest Solver. Available online: https://www.gurobi.com/solutions/gurobi-optimizer/?campaignid=2027425882&adgroupid=77414946611&creative=601650357813&keyword=gurobi&matchtype=e&_bn=g&gclid=Cj0KCQjwtJKqBhCaARIsAN_yS_kveIGGtCRLCzHsLY0FDlET2Ux6C-pNGkzLnkAZ0v2vxBuAS5dUayIaAmEJEALw_wcB (accessed on 3 November 2023).