Journal of Operation and Automation in Power Engineering

vol. 11, no. Special Issue, Dec. 2023, Pages: 100-105

http://joape.uma.ac.ir

Investigation and Optimization of Wind Turbine and Photovoltaic Hybrid System Taking into Account Economic and Energy Considerations

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Abstract— *This paper introduces a novel model for optimizing renewable energy systems, specifically focusing on the integration of wind turbines and photovoltaic panels to minimize net present value (NPV) costs. Addressing a significant gap in current literature, our model considers both economic and energy factors to design an efficient hybrid system. The key contributions of this study lie in investigating the impact of incentives on cost reduction across various scenarios and proposing an optimization approach utilizing the harmonic search algorithm. In contrast to existing approaches, which often overlook economic considerations, our model accounts for the dynamic nature of electricity prices. Through simulation results, we demonstrate that the cost-effectiveness of renewable energy systems varies with electricity prices. Our findings reveal that in our study area, current electricity prices do not render renewable resources economically viable, highlighting the need for optimization strategies. By employing the proposed method, we determine the optimal configuration of solar panel and wind turbine surfaces to achieve cost-effective energy production. This research not only advances the understanding of renewable energy integration but also provides practical insights for policymakers and industry stakeholders. Overall, our study underscores the importance of considering economic factors alongside technical aspects in designing renewable energy systems.*

Keywords—Renewable energies, incentive cost, harmony search algorithms.

1. INTRODUCTION

In the past few decades, energy consumption in the world has increased rapidly and has caused subterranean problems including reduced fuel reserves and increased pollution worldwide [1, 2]. Due to the limitation of fossil fuels and their environmental impacts, finding alternatives has become necessary. Since the energy from wind and solar sources is not a pollutant and is available free of charge [3, 4] are slightly unlimited, they are the most suitable alternative to fossil fuels. Due to the deficiencies and limitations in the power supply of these types of resources, it is necessary to use these types of resources to be manageable [5–7] especially if the energy system is connected to the network and the storage system is not considered. To use energy, a renewable system needs to be designed optimally effectively, and cost-effectively. Since renewable energy resources are highly dependent on atmospheric conditions, these factors affect the design outcome. One of the other important factors that affect the results of optimal design is the purchase of electricity prices [8, 9]. It is from the network, i.e. at high prices of electricity, the tendency to use renewable resources increases [10].

Numerous studies have delved into optimizing the design of renewable energy combining systems [11, 12]. These endeavors have initially surveyed various combined systems and outlined effective evaluation criteria, often classified as technocratic factors. Subsequently, different methodologies for determining the size of combined systems have been explored, ranging from graphical and analytical methods to more advanced approaches such as artificial and combined structure methods.

A noteworthy body of research focuses on selecting optimal resources to minimize costs while ensuring energy access [13, 14]. For instance, [14] investigates the optimal number and type of resources to reduce total costs and guarantee energy access. The study compares the costs of wind, solar, and diesel systems with and without batteries, offering insights into the cost-effectiveness of different configurations. Similarly, [15] proposes a model with three decision variables aimed at reducing the total cost of the energy system while considering reliability issues.

Moreover, several studies have examined the design of renewable energy combining systems both off-grid and connected to the network [16–18]. For instance, [16] presents a reprocessing model to evaluate equipment sizes for off-grid systems, considering factors such as diesel performance and carbon dioxide emissions. On the other hand, [19] introduces a linear programming model to reduce the cost of energy combining systems connected to the

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Received: 11 Dec. 2023
Revised: 06 Apr. 2024
Accepted: 01 May. 2024
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DOI: 10.22098/joape.2024.14215.2091
Research Paper

network, focusing on determining the optimal number of wind turbines and photovoltaic panels.

In addition to cost considerations, some studies have assessed environmental and economic impacts on a larger scale [20, 21]. For example, [20] compares a renewable energy combined system connected to the network with standard network performance, emphasizing environmental and economic effects. Furthermore, [21] explores designs of energy composition systems with intermittent hydrogen production, estimating the net present value while considering electricity sales to the network.

In [22], a cost-effective on-grid hybrid renewable energy system was optimized for supplying electricity to the Engineering College at the University of Diyala, Iraq. The system achieved an average daily load of 25.0 kWh with a total cost of $5142 and an energy cost of $0.05/kWh, demonstrating lower carbon emissions compared to conventional methods. However, challenges such as intermittency and system maintenance costs may pose disadvantages to widespread adoption. Ref. [23] introduces a novel optimization strategy for hybrid-renewable energy systems in microgrids, aiming to minimize the levelized cost of energy (LCOE) and loss of power supply probability (LPSP) while maximizing renewable energy source (RES) utilization. Combining the Taguchi method with a fuzzy decision-maker-based multi-objective optimization algorithm, the strategy optimizes energy source usage, determines decision variable bounds, and sizes renewable energy sources. Applied to microgrid design scenarios in Sønderborg, Denmark, the strategy yielded promising results, yet challenges such as complexity and computational demands may limit widespread application. Ref. [24] proposes a hybrid renewable energy system integrating photovoltaic, wind, and concentrated solar power, alongside two cogeneration models, evaluated based on the levelized cost of energy (LCOE) and loss of power supply probability (LPSP). Through multi-objective optimization utilizing Xining City's natural resources, the optimal system configuration and dynamic dispatch strategy are determined. Results indicate that both cogeneration modes effectively meet power output requirements, with varying LCOE and LPSP values depending on storage system implementation. Additionally, the analysis underscores the significance of affordable electric energy storage for ensuring a stable energy supply in hybrid systems. While the existing literature offers valuable insights, there remains a need for comprehensive evaluations that incorporate both economic and environmental considerations, especially in the context of optimizing wind turbine and photovoltaic hybrid systems for cost-effective energy production.

This research significantly contributes to the field by delving into the optimal design of renewable energy combining systems connected to the network, with a specific focus on photovoltaic panels and wind turbines, across varying electricity prices. By considering the possibility of selling excess power to the grid and unsupplied purchase, the study enhances the economic feasibility of such systems. Furthermore, the research employs physical models and hourly simulations, leveraging the harmonic search algorithm to optimize system size and reduce overall costs. Notably, the defined steps for utilizing the harmonic search algorithm facilitate practical implementation and cost-effectiveness. Through a detailed case study of a housing complex in Mahan city, Kerman province, the manuscript illustrates the real-world applicability and feasibility of the proposed approach. Additionally, by spotlighting Yazd city's geographic relevance, situated at 30 degrees latitude and 57 degrees longitude, the research underscores regional considerations in renewable energy system design and implementation. In summary, the main contributions of this paper are as follows:

- Investigates optimal design of renewable energy combining systems with a focus on photovoltaic panels and wind turbines
- Considers economic feasibility by analyzing selling excess power to the grid and unsupplied purchase
- Utilizes physical models and hourly simulations to optimize system size and reduce costs, employing the harmonic search algorithm

2. MATERIALS AND METHOD

2.1. Structure of combined energy system

Fig. 1 shows the structure of the proposed combined system. In this system, it is assumed that the optimal power follow-up exists in both photovoltaic and wind systems and both systems work in the highest power.

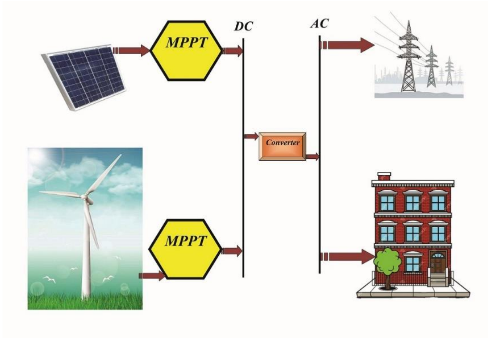

Fig. 1. Structure of combined energy system.

In order to simulate the system, hourly information including wind speed, radiation intensity and consumption load during one year is required. The meteorological data used in this study were prepared from Yazd meteorological department. The average daily consumption per month is obtained through electricity bill and then by estimating the daily power consumption pattern for one day of each month, hourly electricity consumption information is estimated by MATLAB software.

2.2. Formulation

A) Economic modeling

The total cost of the system includes the initial investment cost, the net present value of maintenance costs, the cost of the depreciation and payment to the network minus the cost received from the network for the sale of power to the network. In this research, assuming the project life expectancy equals N years, interest rate r, and inflation rate δ, the total cost of equipment is calculated below.

Assuming the initial investment cost is equal to α_n annual maintenance costs equal to OM, and the value of diffusion equal to α_{OM_n} per square meter, total investment cost and total net worth of maintenance and income from diffusion are calculated using Eqs. (1) to (3), respectively.

$$I_n = \alpha_n \times \mathrm{A}_n \tag{1}$$

$$OM_{\mathrm{NPV}_n} = \alpha_{\mathrm{OM}_n} \times \mathrm{A}_n \times \sum\nolimits_{k=1}^{N} \left(\frac{1+\varepsilon_n}{1+r}\right)^k \tag{2}$$

$$S_{NPV_n} = S_n \times \mathrm{A}_n \times \left(\frac{1+\delta}{1+r}\right)^N \tag{3}$$

That n represents the type of equipment (photovoltaic panel and wind turbine) and ε_n is the annual price increase rate of the equipment. In the case of the annual electricity purchase fee network from the network (C_a) and the annual revenue from the sale of electricity to the network (Ia) must be determined.

Table 1. Electricity prices in Yazd province for household loads.

Monthly use (KWH)	Price ($/kWh)
0 to 100	0.012
Surplus from 001 to 002	0.014
Surplus from 002 to 003	0.03
Surplus from 003 to 004	0.053
Surplus from 004 to 005	0.061
Surplus from 005 to 006	0.077
Surplus from 006	0.085

The price of electricity consumed by domestic consumers is listed in the Table 1 according to the decree of the Ministry of Energy in 2015. [17] The method of calculating the cost of electricity consumed and the proceeds of its sale to the network is explained below.

Assuming that the monthly electricity consumption in each house is constantly equal to E, the cost of purchasing shared electricity per month is calculated according to Eq. (4).

$$C_m = f\left(E_{b_m}\right) \times P_a \tag{4}$$

In which, f is the function regarding E_b and according to the price of Table 1, Calculates the price of electricity at the current price. P_a is a coefficient that can be calculated by changing the cost of electricity consumption at different prices ($P_a = 1$ is related to the current price of electricity.) Therefore, the annual cost of purchasing electricity from the network is calculated using Eq. (5).

$$C_a = \sum\nolimits_{m=1}^{12} C_m \tag{5}$$

Assuming the price of selling electricity to the network equals P_s, the proceeds of the sale of additional power generated by renewable resources to the network are calculated by Eq. (6).

$$I_a = P_s \times \sum\nolimits_{t=1}^{T} e_s\left(t\right) \tag{6}$$

In which, $e_s(t)$ is the amount of energy sold at the time of t in kWh unit, and T is the number of hours in one year (T=8760).

The net present value of electricity purchase costs from the network and the income from electricity sales are calculated from Eqs. (7) and (8), respectively.

$$C_{NPV_g} = C_a \times \sum\nolimits_{k=1}^{N} \left(\frac{1+\delta}{1+r}\right)^k \tag{7}$$

$$I_{NPV_g} = I_a \times \sum\nolimits_{k=1}^{N} \left(\frac{1+\delta}{1+r}\right)^k \tag{8}$$

B) Objective function

By calculating the net present value of all costs, the objective function can be expressed as Eq. (9).

$$F = I + OM_{NPV} - S_{NPV} + C_{NPV_g} - I_{NPV_g} \tag{9}$$

In these equations, I is the cost of investing equipment, OM_{NPV} and S_{NPV} are the current net worth of repairs and maintenance costs and income from equipment scraps, respectively, and two variables C_{NPV} and I_{NPV} are the net present value of electricity purchase costs from the network and annual revenue from energy sales per unit of dollars, respectively.

2.3. Mathematical modeling of the system

To simulate system equipment, it is necessary to model each component of the system mathematically. Then, the system component model is described. The power generated by a set of photovoltaic panels can be calculated using Eq. (10) [8].

$$P_{PV}\left(t\right) = R\left(t\right) \times \eta_{PV} \times A_{PV} \tag{10}$$

That η_{PV} is the Panel Efficiency A_{PV} is the total set area of panels in m_2 and R(t) is the intensity of sunlight in terms of kW/m^2. The power generated by a wind turbine can be calculated from Eq. (11) [8].

$$\begin{array}{cc} P_r \frac{V(t)^3 - V_{ci}^3}{V_r^3 - V_{ci}^3} & V_{ci} \leq V\left(t\right) < V_r \\ P_W\left(t\right) = P_r & V_r \leq V\left(t\right) < V_{co} \\ 0 & O.W. \end{array} \tag{11}$$

V_{ci}, V_r, and V_{co} are low cut-in speeds, rate, and cut-out speeds of turbines and P_r power, respectively. Nominal power is defined as a function of the area occupied by turbine blades (Aw), air density (ρ_a), power coefficient (C_p), wind turbine generator efficiency (η_g), and gearbox efficiency as Eq. (12).

$$P_r = \frac{1}{2} \times C_p \times \rho_a \times \eta_g \times \eta_r \times A_W \times V_r^3 \tag{12}$$

Wind speed information is recorded at a certain altitude, so it is necessary to estimate the wind speed information at the height of the wind turbine towers. To achieve this, the wind profile power law Eq. (13) is used.

$$\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^a \tag{13}$$

Where u is the wind speed at the desired height, your wind speed turns out in the reference height of z_r and a is a roughness coefficient.

2.4. Power control strategy

Assuming that the power generated from renewable sources equals P_g, the power consumption load equals Pl, and the conversion efficiency of renewable resources equal to the η_{inv}, the power controlling strategy can be summarized as follows:

If $P_g\left(t\right) > P_L(t)/\eta_{inv}$, the load is fully provided and additional power is injected into the network. Additional power value is calculated from Eq. (14).

$$e_s\left(t\right) = P_g\left(t\right) \times \eta_{inv} - P_L\left(t\right) \tag{14}$$

If $P_g\left(t\right) < P_L(t)/\eta_{inv}$, so the load is not fully supplied and some power is received from the network, which is calculated from Eq. (15).

$$e_b\left(t\right) = P_L\left(t\right) - P_g\left(t\right) \times \eta_{inv} \tag{15}$$

2.5. Case study

Parameters and outputs

The information used in this case study is demonstrated in Table 2. Information on radiation intensity, wind speed, and consumption load during one year are presented in Figs. 2 to 4:

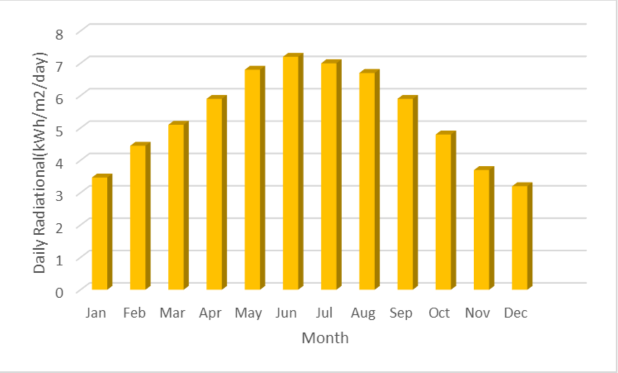

Fig. 2. Intensity of solar radiation over a year.

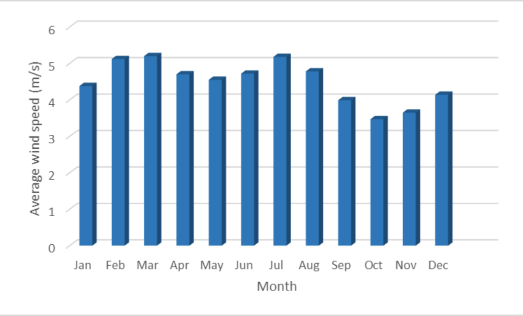

Fig. 3. Wind speeds over a year.

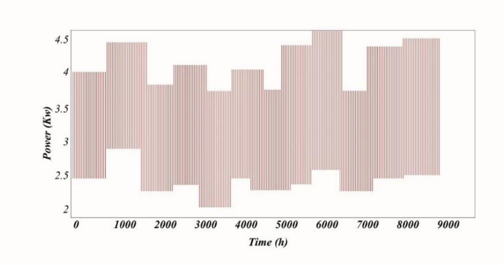

Fig. 4. Power consumption load over a year.

3. RESULTS

The proposed model for the optimal design of the combined system in MATLAB software has been implemented in two scenarios. The price of electricity in Iran is not the real amount and in the past years, it has been observed that the price has been increasing. Therefore, in each scenario, the proposed model has been investigated at different electricity prices and the results are compared with the case where a set of housing units receives the total power from the network.

A) *First scenario*

In the first scenario, where the network functions as a storage system, we conducted simulations to analyze the cost-effectiveness of utilizing photovoltaic panels and wind turbines at different electricity prices. The optimal equipment configurations at varying electricity prices are illustrated in Fig. 5. Our findings revealed that at lower electricity prices (Pa values less than 2.2), the utilization of renewable resources was less cost-effective. This observation was further supported by the cost analysis presented in Table 3, which demonstrated that energy production from wind turbines is relatively more expensive compared to photovoltaic sources. Consequently, the system tends to prioritize the use of photovoltaic sources over wind turbines in such scenarios.

However, as illustrated in Fig. 6, as the value of Pa increases and photovoltaic installation becomes more prominent, the overall cost of the system utilizing renewable resources becomes less than that of conventional energy sources. This highlights the cost reduction achieved through the utilization of renewable resources in the system.

Table 2. Parameters used in a case study.

Economic parameter	Interest rate	γ	0.1
	Inflation rate		0.04
	Escalation rate	ε_N	0.075
	Project life time	N	20
Solar Panel	initial cost (\$/m^2)	α_{PV}	519.7
	The cost of repair and yearly maintenance(\$/m^2)	$\alpha_{OM_{PV}}$	%1
	Sell price(\$/m^2)	S_{PV}	%25
	Life time	L_{PV}	20
	Efficiency	η_{PV}	0.14
Inverter efficiency	Efficiency	η_{tnv}	0.9
Wind turbine	Initial cost(\$/m^2)	α_W	544.2
	The cost of repair and yearly maintenance(\$/m^2)	α_{OM_W}	%2
	Sell price(\$/m^2)	S_W	%30
	Life time	S_W	20
	Generator efficiency turbine	η_g	0.85
	Gearbox efficiency	η_r	0.85
	Power coefficient	C_p	0.59
	Power coefficient(kg/m^3)	ρ_a	1.225
	Roughness coefficient	α	0.2
	V_{Cutin}(m/s)	η_g	1.5
	V_{Cutout}(m/s)	η_r	25
	Nominal power(kW)	C_p	1
Grid	Fixed price of electricity sales(\$/kWh)	P_s	0.131

Table 3. Cost of production of the power unit of equipment.

source	Annual energy (kWh/m^2)	Net present value (\$/m^2)	Cost of production of the power unit (\$/kWh)
Photovoltaic	184–585	955.57	0.890
Wind	812–991	366.35	0.561

Additionally, our analysis acknowledges the limitations, challenges, and uncertainties associated with our proposed method. These include factors such as variability in renewable resource availability, technological constraints, and potential regulatory barriers. By considering these factors, we aim to provide a comprehensive assessment of our findings.

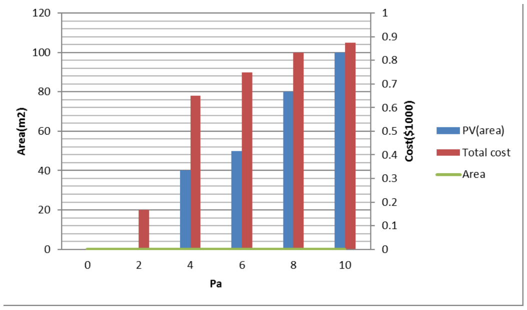

Fig. 5. The optimal size of the equipment and the net present value of total cost in the first scenario.

B) *Second scenario*

In this scenario, where extra power is sold to the network at a fixed price, resulting in income for consumers, we conducted simulations to assess the optimal design of the energy combining system. The results of the optimal design are presented in Figs. 7 and 8. Similar to the previous scenario, our findings indicate that the use of renewable resources becomes more cost-effective as electricity prices (Pa values) increase. However, it is observed that despite the more expensive power generation from wind turbines, the storage system cannot effectively store this energy. This limitation underscores the need for advanced storage solutions or alternative strategies to maximize the utilization of wind energy in the system. Additionally, since photovoltaic power generation is not feasible during nighttime hours, the system tends to rely on wind turbines at higher Pa values (7.8). These observations highlight the dynamic nature of system optimization under varying conditions

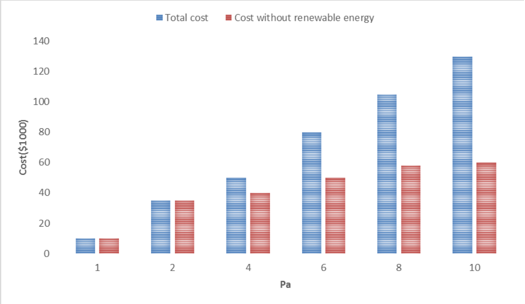

Fig. 6. Comparison between the net present value of the total cost of the combined system and the state where the system's electricity is provided only from the network in the first scenario.

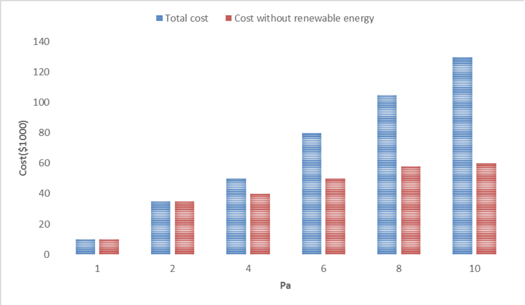

Fig. 7. Optimal equipment size and the net present value of total cost in the second scenario.

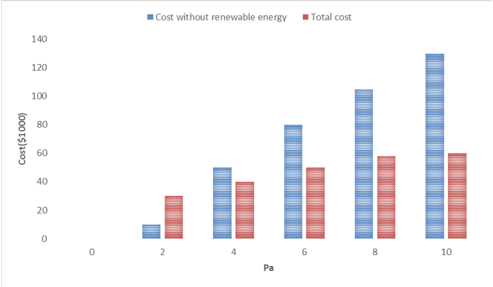

Fig. 8. Comparison between the net present value of the total cost of the combined system and the state where the system's electricity is provided only from the network in the second scenario.

and emphasize the importance of considering both technical and economic factors in system design. Furthermore, it underscores the necessity for robust storage solutions and strategic utilization of renewable resources to ensure optimal system performance and cost-effectiveness across different scenarios.

4. DISCUSSION

In the first scenario, where the network functions as a storage system, our simulations revealed that the cost-effectiveness of utilizing renewable resources is dependent on electricity prices (Pa values). At lower Pa values, renewable resource utilization, particularly from wind turbines, was found to be less cost-effective due to the relatively higher cost of energy production compared to photovoltaic sources. Consequently, the system tended to prioritize the use of photovoltaic sources over wind turbines in such scenarios. However, as Pa values increased, the overall cost of the system utilizing renewable resources became less than that of conventional energy sources, indicating the potential for cost reduction through the utilization of renewable resources.

In the second scenario, where extra power is sold to the network at a fixed price, our simulations revealed similar trends in renewable resource utilization. However, a notable difference was observed in the utilization of wind turbines. Despite the higher cost of energy production from wind turbines compared to photovoltaic sources, the storage system was unable to effectively store this energy. Consequently, the system tended to rely more on wind turbines, especially at higher Pa values where photovoltaic power generation is not feasible during nighttime hours.

Comparing the results of the two scenarios, we observe that while the overall trend in renewable resource utilization is similar, there are differences in the specific utilization patterns of photovoltaic panels and wind turbines. In Scenario 1, the system prioritizes photovoltaic sources over wind turbines due to their lower cost of energy production. However, in Scenario 2, the system tends to rely more on wind turbines, particularly at higher Pa values where photovoltaic power generation is limited.

Overall, these findings underscore the dynamic nature of system optimization and highlight the importance of considering both technical and economic factors in renewable energy system design. Furthermore, they emphasize the need for robust storage solutions and strategic utilization of renewable resources to ensure optimal system performance and cost-effectiveness across different scenarios.

5. CONCLUSION

The presented method has been applied as a case study to a housing complex consisting of 6 houses located in Mahan city of Kerman province whose electricity is currently provided only by the network. In this study, it has been shown that at the current price of electricity in none of the scenarios, the use of renewable resources is not cost-effective and at higher prices, the use of photovoltaic will be cost-effective and in the case of wind resources. The cost of power generation is higher than that of photovoltaic, and since it is possible to store power in the first scenario, then at no cost of electricity is the use of wind turbines. It is not economical and in the case of the second scenario that it is not possible to store power and since photovoltaic power generation is not possible during some hours of the day, it is not possible to use wind turbine at a high price.

Funding: No funding for this research.

Data Availability Statement: All data used to support the findings of this study are included within the article.

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

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