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TECHNIQUES FOR EFFECTIVE MODELING AND SIZING OPTIMIZATION IN HYBRID PHOTOVOLTAIC-WIND POWER GENERATION SYSTEMS

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ABSTRACT

The world's population is increasingly industrializing, which has led to an increase in the need for energy, particularly electricity. In order to manage energy efficiently, this work optimises the modelling and sizing of hybrid photovoltaic (PV) and wind turbine (WT) systems. It assesses system performance in various climates using mathematical models for wind speed, turbine performance, and PV electricity generation. Methods such as Weibull probability distribution, wind power law, and Maximum Power Point Tracking (MPPT) are utilised. Cost, output, and lifespan analyses are performed on six WT and PV models to provide a balanced, sustainable power solution with optimal performance and cost.

Keywords: Photovoltaic, Wind power, Renewable Energy, Fossil Fuels, Solar Energy, photovoltaic-wind power systems

1. INTRODUCTION

Given the variability and correlations between solar and wind resources, accurate modelling of these resources is necessary for effective sizing and operation in hybrid photovoltaic-wind power systems. In order to reduce costs, maximise the use of renewable energy sources, and balance the production and consumption of energy, suitable components like as solar cells, wind turbines, and energy storage units must be chosen. The size of the system must be adjusted. Grid integration, dependability, and economic viability can all be taken into account when determining the ideal design, which can be done with the help of optimisation techniques like genetic algorithms and particle swarm optimisation.

1.1. Hybrid Photovoltaic-Wind Power Generation Systems

Solar and wind energy are combined in hybrid photovoltaic-wind power generation systems to produce a more dependable and effective renewable energy source. Solar energy is captured by photovoltaic (PV) panels to create electricity, and wind energy is captured by wind turbines to create power. Hybrid systems can benefit from the complementing qualities of solar and wind energy by combining the two; solar electricity is typically more abundant during the day and in the summer, while wind energy is frequently more available at night or in the winter. System reliability is increased by this complementary relationship, which helps guarantee a steady energy supply even in the event that one source is sporadic.

Hybrid systems not only increase overall efficiency and decrease the demand for energy storage or backup systems, but they also improve energy reliability. This configuration is especially helpful in isolated or off-grid areas where having access to a reliable energy source is essential. The location, the type of weather, and the proper sizing of the components (batteries, wind turbines, PV panels, and inverters) all affect how well the system works. Hybrid photovoltaic-wind power generation systems can contribute to the larger objectives of renewable energy development and lessen reliance on fossil fuels by optimising the system design and providing an affordable, sustainable energy option with less environmental impact.

1.2. Modeling and Simulation of PV-Wind Hybrid Systems

The development of renewable energy sources is constantly progressing because of the precarious state of industrial fuels, such as gas, oil, and others. This is the rationale behind the increased significance of renewable energy sources in modern times. A few more benefits are that it's recyclable, eco-friendly, and widely available in nature. Numerous renewable energy sources exist, including tidal, wind, sun, and hydropower. The two renewable energy sources that are expanding the quickest in the globe are solar and wind power. PV cells and wind energy conversion are used to convert energy without emitting any pollutants.

Electricity use is on the rise daily. Presently operational base load units are unable to satisfy electricity demand. By employing a variety of energy sources, supply and demand can be balanced at peak loads. Isolated areas that do not have access to conventional power sources can also make use of small-scale standalone power generation systems like these.

The hybrid system is contained the wind and PV systems working in tandem. The PV system's power source, solar energy, is promptly accessible in nature. The photovoltaic (PV) energy system comprises of PV modules and greatest power point tracking systems. The course of solar energy collecting includes changing over the light that raises a ruckus around town cells into electricity. Using the most extreme power point tracking system related to the Perturb and absorb algorithm considers the extraction of the best power from the PV modules. An ac-dc converter changes alternating current (ac) into direct current (dc).

An AC/DC converter, gearbox, wind turbine, and generator are used to generate power from wind. A wind turbine converts wind mechanical energy into rotational mechanical energy in order to produce electricity. At the turbine shaft, a generator is used to convert this mechanical energy into electrical energy. In order to get the most out of the wind system, we used a maximum power point tracing mechanism.

A bi-directional converter is used with both energy systems to charge a battery. The battery and the bidirectional converter together make up the common additional load for PV and wind energy systems.

The reliability of load demands can be consistently improved by hybrid generation systems that use multiple power sources. A hybrid system can produce even greater producing capacities. A standalone system can reliably provide the load with output that is unaffected by weather conditions. In order to convert the energy produced by the PV system into storage energy and allow the wind turbine to generate electricity constantly, an efficient means of energy storage, like a battery bank, is required.

1.3. Applications of Hybrid PV-Wind Systems

➢ Remote and Off-Grid Locations

Due to its capacity to produce power in regions with restricted grid access, hybrid PV-wind systems are especially well-suited for isolated and off-grid sites. By eliminating reliance on fossil fuels and enhancing quality of life, these systems can offer island people a dependable and sustainable power source. Hybrid systems have the potential to enable access to vital services like healthcare, education, and communication in remote places by bringing energy to previously underserved people. Hybrid systems can provide an economical and ecologically responsible means of supplying electricity to remote industries like mining and agriculture.

➢ Grid-Connected Systems

Hybrid PV-wind systems have the potential to significantly increase grid stability and dependability when incorporated into the system. By supplying extra power during times of high consumption, they can assist in controlling peak load demand and minimize the need for additional power plants. Furthermore, energy storage using hybrid systems can assist balance supply and demand and lessen dependency on fossil fuels by storing excess energy for later use. Hybrid systems have the capacity to supply backup power in the case of emergencies or grid disruptions, guaranteeing the continued operation of critical services.

➢ Residential and Commercial Applications

Due to their many advantages, hybrid PV-wind systems are becoming more and more common in both residential and commercial settings. These systems can help businesses and households become more self-sufficient by enabling them to produce their own electricity and lessen their dependency on the grid. Over the long run, this can bring about tremendous cost reserve funds for the two people and organizations as their electricity bills can be diminished. As well as advancing the utilization of renewable energy sources and decreasing fossil fuel byproducts, hybrid systems are better for the climate.

- **Microgrids and Community Energy**

Microgrids are little, localized energy systems that can work freely or working together with the primary matrix. Communities can make microgrids with hybrid PV-wind systems, which offer a more economical and solid electricity source. When there are emergencies or grid outages, these microgrids can be especially helpful in keeping vital services running. Additionally, by giving communities more authority over their energy resources, microgrids can promote community empowerment. Additionally, they can promote local energy-related sectors and provide jobs, which will boost economic development.

- **Emerging Applications**

Hybrid PV-wind systems are discovering novel and inventive uses as technology progresses. The charging of electric vehicles is one such application. As electric vehicles become more and more common, hybrid systems can supply the power required to maintain the infrastructure for charging them. Hybrid systems can power water pumping and desalination facilities in dry places, alleviating the problem of water scarcity. Hybrid systems can also produce hydrogen, a clean fuel source for industry and transportation that will help ensure a more sustainable energy supply in the future.

2. LITERATURE REVIEW

Bansal, A. K. (2022) offered a conceptual framework for modelling, sizing optimisation software, renewable energy sources, hybrid system optimisation criteria, control techniques, and hybrid system implementation. This research also provided a mathematical model of the components of the hybrid system, emphasising the importance of system cost and power reliability. It also compares the most often used topologies for HRES implementation and sizing. A thorough analysis of the several software tools and methods used in size optimisation was included in the conclusion of this article. The several uncertainty analyses in HRES size optimisation were then included in the study.

Ghaithan, A. M., & Mohammed, A. (2022) suggested a new optimisation model for the sizing of a solar-wind-grid-connected system that is based on a mixed-integer linear programming technique. The goal of the suggested hybrid system is to meet the load requirement of a Saudi Arabian industrial facility. The proposed model calculates the ideal hourly energy obtained from the grid and hourly excess energy generated by the system and sold to the grid, as well as the ideal number of wind turbines and solar modules. According to the model's results, in addition to the grid, 77 solar modules and 7 wind turbines are required to meet the load requirement. The yearly output of the system was 450,734 kWh, or 82% of the total annual load usage. Additionally, the system generated 72,752 kWh of excess energy, bringing in $6,184 for the industrial complex. Taking into account an off-grid photovoltaic-wind system with battery storage enhances the case study. The findings indicated that adding battery storage raises the hybrid system's energy costs. When compared to the grid-connected system, which will remove around 225,768 kg of carbon dioxide annually, the off-grid photovoltaic-wind system exhibits good results in terms of environmental concerns. It will remove approximately 279,800 kg of carbon dioxide annually. To determine how the cost of power would affect the best system design and the cost of energy from the hybrid system, a sensitivity analysis was performed.

Fares, D., Fathi, M., & Mekhilef, S. (2022) provides an analysis of the performance of 10 metaheuristic optimisation strategies used to address the sizing problem for a standalone hybrid renewable energy system that consists of a battery, a wind turbine, and a photovoltaic module (PV/WT/Battery). The algorithms included the following: moth flame optimisation (MFO), brainstorm optimisation in objective space (BSO-OS), genetic algorithm (GA), cuckoo search (CS), simulated annealing (SA), harmony search (HS), Jaya algorithm, firefly optimisation algorithm (FA), flower pollination algorithm (FPA), and the simplified squirrel search algorithm (S-SSA). The goal of the optimisation procedure is to keep the system's acceptable power supply probability (DPSP) deficiency while minimising its total net present cost (TNPC). Additionally taken into account are the relative excess power generated criterion and the levelized energy cost. The examined algorithms have been performed 50 times each for each of the four DPSP values (0%, 0.3%, 1%, and 5%). With zero standard deviation and a 0% rise in the TNPC values over the optimal solutions, FPA and SA showed excellent robustness and accuracy based on the simulation findings. With an average execution time of 6.32 seconds, the FAO performed the best, followed by BSO-OS (6.36 seconds) and SA (7.84 seconds). The SA is determined to be the optimal solution for resolving the sizing issue since it offers the optimum balance between robustness, accuracy, and speed. When the execution time is not critical to the optimisation, the FPA is the most beneficial. Our results will serve as a useful guide for researchers choosing the optimal method for the sizing challenge.

Mahesh, A., & Sushnigdha, G. (2022) demonstrate how integrating EVs into the system lowers costs when taken into account during the sizing stage in the second scenario and increases dependability in the first. This study takes into account the modified SSR algorithm because of its capacity to search efficiently in multi-modal issues. According to the obtained data, the LCE can be decreased by up to 6.85% in the first scenario when EVs are introduced after sizing, and by nearly 8% in the second situation when EVs are taken into consideration throughout the sizing process. Additionally, the outcomes of the modified SSR algorithm were contrasted with those of the particle swarm optimisation, grey wolf optimiser, and the original SSR method. The outcomes also show that a better solution can be obtained with fewer iterations using the enhanced SSR method.

Riaño, C., Florez, E., & Peña, C. (2021) intends to create a hybrid system sizing method based on locally obtained environmental data in order to design a system that optimally utilises the local natural resources. The local environmental conditions are gathered using a data gathering system, the energy demand is used to determine the system requirements, and a mathematical model of the electrical behaviour is searched for. The model ensures appropriate dimensioning for a steady supply of low-power energy suitable for residential usage by enabling analysis of the system's behaviour under various environmental circumstances in the area. This article offers an alternate method of characterising a hybrid power generating system (photovoltaic/wind turbine) using data gathered on-site. When appropriately processed, this data enables the sizing of a hybrid system that is better suited to the environmental conditions. The University of Pamplona's experimental farm in northern Colombia is where the system was put into practice. This plan served as the foundation for the efficient design and installation of a hybrid system to fulfil energy demands.

3. RESEARCH METHODOLOGY

Creating a thorough mathematical model for a hybrid photovoltaic (PV) and wind turbine (WT) power generation system was the main goal of the research technique. The method comprised a thorough examination of all system components, such as photovoltaic power generation, wind speed correction, wind turbines, and the Weibull probability density function. Examining the system's performance and optimizing its sizing for efficient power management was the main objective.

First, an analysis was conducted on six distinct wind turbines that are frequently utilized for modest wind power applications in the USA and Europe. These turbines were chosen based on the rated power output at 12.5 m/s wind speed and the associated expenses. The usual tower height of thirty meters was used to model these turbines. Market pricing and power ratings for every turbine were gathered, combined, and subjected to analysis.

The recorded wind speed data was then adjusted using the wind power law and the wind speed correction model to the desired hub height. This adjustment, which set the wind shear exponent to one-seventh for open ground conditions, took into consideration changes in wind speed at different heights. Precisely forecasting the wind turbines' output power required the revised wind speed values.

At the chosen location, a Weibull (PDF) was employed to simulate the distribution of wind speeds. The form (β) and scale (η) elements of the Weibull PDF were calculated using historical wind speed data. The scale component depicted the site-wide distribution of wind speeds, while the shape component dictated the form of the curve. The turbine power curve and this model might be used to determine the likelihood of wind speed and the energy output of wind turbines.

The turbine power curve supplied by the manufacturers was used to calculate the energy output from the wind turbines. Using the wind speed data and the Weibull PDF, the energy production was computed. This computation required figuring out how many days, how many hours, and how long each wind turbine will run for. The end product was a thorough assessment of the energy produced by the wind turbines at the designated location.

For the hybrid system, six distinct photovoltaic (PV) generators were chosen and installed in simultaneously. We gathered and examined information on the prices and power ratings of various photovoltaic modules. For the PV modules, a mathematical model that took into account the impact of temperature and irradiance levels on the output power was created. The Maximum Power Point Tracking (MPPT) controller model was used to simulate each PV array's performance and forecast the power production under various environmental circumstances.

4. DATA ANALYSIS

A hybrid photovoltaic (PV) and wind turbine (WT) system's component data is examined to provide the best possible power management and sizing plan. Mathematical modeling of wind turbines, wind speed, and solar power generators is used to assess the system's performance. Several models are used in this analysis, such as those that describe the energy production of wind turbines, the performance of PV modules in various climates, and the Weibull probability density function for wind speed.

4.1. The wind Turbine Model

Table 1 displays the six possible variations of WTs. For minor wind power applications, the USA and Europe are the regions where these WTs are most frequently employed. It has been suggested that all turbines use a 30-meter tower.

Table 1: The cost and rating of small wind turbines

	Small wind turbine parameters			
Types of wind Turbine	Product	Turbine MSRP (US$)	Tower price (US$)	Watt at 12.5 m/s
1	SouthWest (Air X)	590	805.02	390
2	SouthWest (Whisper 100)	2.102	805.02	890
3	SouthWest (Whisper 200)	2.398	805.02	990
4	SouthWest (Whisper 500)	7.106	1162.21	2990
5	SouthWest (Skystream 3.7)	5.395	1162.21	1770
6	Aeromax Engineering	1.588	803.00	780

A comparison of small wind turbines with respect to price and power output at 12.5 m/s wind speed is shown in Table 1. The SouthWest (Air X) is the most affordable model at $590, producing 390 watts, while the SouthWest (Whisper 500) is the most costly at $7,106, producing 2,990 watts. There are six turbine models available. Depending on the model, tower costs might range from $803 to $1,162. A turbine with 780 watts of power and a price of $1,588 is provided by Aeromax Engineering as a mid-range option.

4.2. Wind Speed Height Correction

It is necessary to apply the wind power law to the anemometer data obtained at a reference height (hr) in order to get the desired hub center (h). The following expression can be used for this purpose:

$$V_h = V_{hr}\left(\frac{h}{h_r}\right)^{\alpha} \quad (1)$$

Where:

- V_h is the wind speed at the desired hub height h,
- V_{hr} is the wind speed at the reference height h_r,
- α is the wind shear exponent (typically between 0.1 and 0.3, depending on terrain and atmospheric conditions),
- h is the desired hub height,
- h_r is the reference height (where the wind speed data was measured).

4.3. Weibull Probability Density Function (PDF)

The most practical way to describe wind speed variability is using the probability density function (pdf). The likelihood that an event will transpire between two endpoints was computed by the pdf. The shape and height of the (PDF) curve demonstrate that the area under the curve is exactly 1 from 0 to infinity. Wind speed thus varies from zero to infinitesimally small (m/s). Publications refer to Weibull pdf using a different terminology. The Weibull PDF is defined in this study as:

$$F(v) = \frac{\beta}{\eta}\left(\frac{v}{\eta}\right)^{\beta-1} e^{-\left(\frac{v}{\eta}\right)^{\beta}} \qquad (2)$$

where v is the wind speed and b is the form factor. For various values of g in equation (8), the plots of b against v and g against v are displayed in Figures 2 and 1, respectively. Because it establishes the curve's shape, the value of b is frequently referred to as the shape factor. Reduced form factor indicates that wind speed dispersion is around average. Using the scale factor (g), we can see where and how wide the bulk distribution is. Figure 4 displays the Weibull probability distribution function for the wind speed profile displayed in Figure 3.

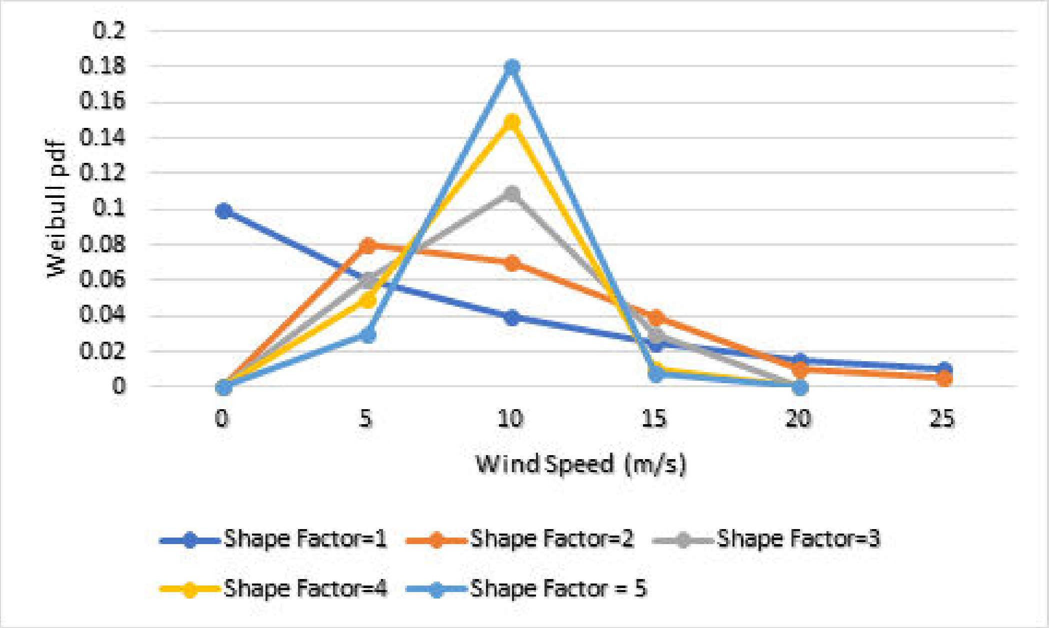

Figure 1: Weibull PDF with form factor b = 1, 2, 3, 4, 5, and scale factor g = 10.

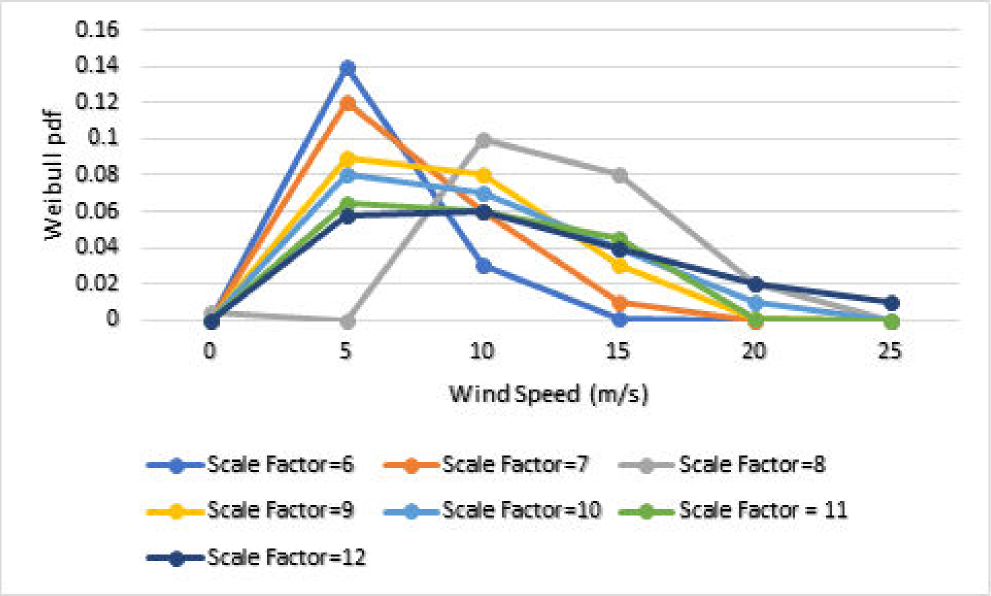

Figure 2: Weibull PDF with scale factor g = 6, 7, 8, 9, 10, 11, and 12 and shape factor b = 2.

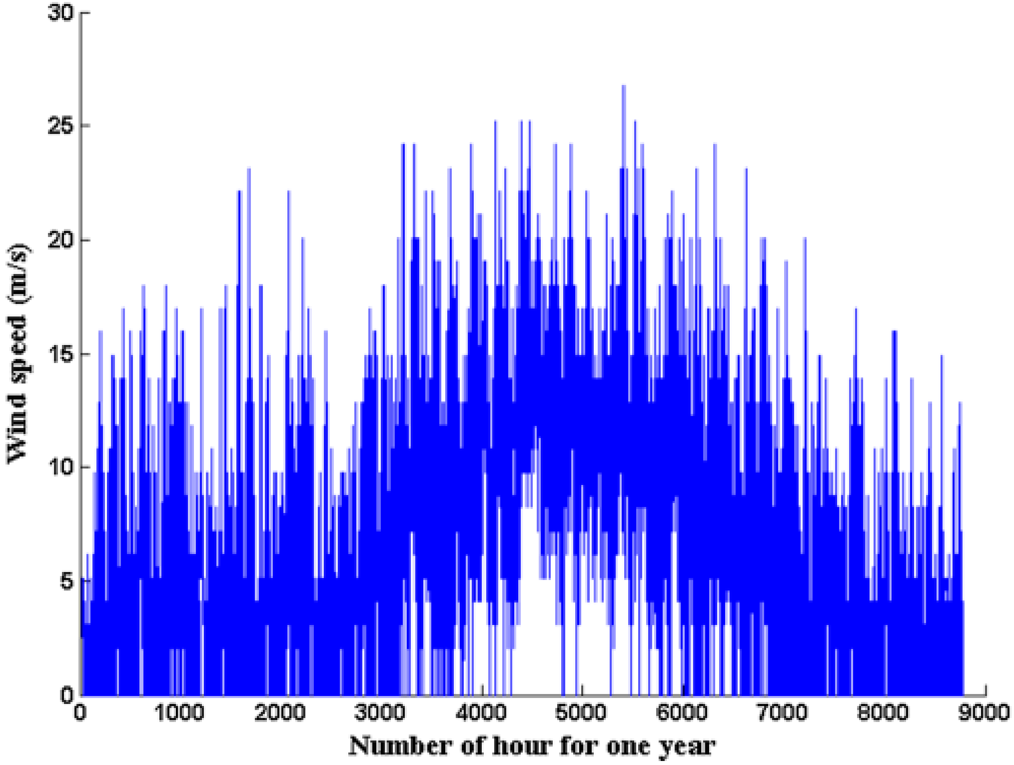

Figure 3: Wind speed conditions due to weather

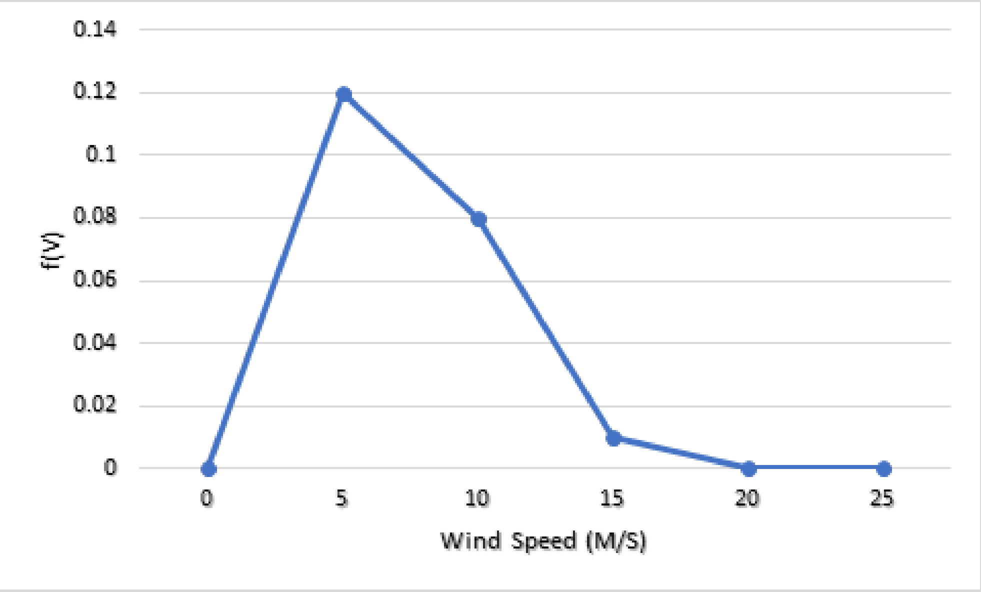

Figure 4: Probability density function of Weibull type [f(v)]

4.4. Wind Turbine Output Energy

One way to find out how much wind power a specific area can produce is to utilize the probability distribution function. An approximation of the wind turbine's power output can be made using the power curve. Usually, a power curve that displays the wind turbine's output power at any wind speed is included by the manufacturer.

For a wind speed profile, the available energy can be computed as

$$E_{wt} = (days)(hours).P_c f(v,\beta,\eta) \qquad (3)$$

where Ewt is the location-specific wind turbine's kilowatt-hour output. The total number of hours during the simulation can be calculated by multiplying the total number of days by the total number of hours; Here, Pc is the wind turbine's power output, and f(v) is the Weibull PDF of the wind speed. V. β stands for the form factor, while g represents the scale factor.

4.5. Photovoltaic (PV) Generator Model

A system that uses photovoltaic cells to transform sunlight into electrical energy is known as a photovoltaic (PV) generator model. These types are made up of solar modules that collect solar radiation and transform it into DC electricity. This DC electricity can then be reversed to AC electricity and used in utility systems, homes, or businesses. The power output at Standard Test Conditions (STC), which is commonly expressed in kilowatts (kW) and represents the maximum amount of energy generated under optimal sunshine, temperature, and air conditions, determines the rating of each PV generator model. Cost, efficiency, and longevity of PV generator models vary; several are built to last for a robust 20 years. These systems are essential for renewable energy solutions, especially when combined with additional energy sources like wind or battery storage to create hybrid systems that guarantee a steady, sustainable power supply.

Table 2 presents the statistics for the six potential PV generators that are part of the system. A single of these PV generators, with an anticipated 20-year lifespan, is combined with each hybrid system.

Table 2: Photovoltaic (PV) Generator Model at STC Rating, Cost, and Lifespan

Types of Solar Modules	Product	Module MSRP (US$)	Tower Price (US$)	Power at STC (kW)	Lifespan (Years)
1. Kyocera Solar (KC200)	KC200	790	190	0.17	20
2. BP Solar (SX 170B)	SX 170B	729.02	160	0.21	20
3. Evergreen (Spruce ES-170)	Spruce ES-170	730.98	160	0.21	20
4. Evergreen (Spruce ES-180)	Spruce ES-180	772.98	170	0.2	20
5. Evergreen (Spruce ES-190)	Spruce ES-190	821	180	0.21	20
6. Solar World (SW-165)	SW-165	710.02	170	0.2	20

Six photovoltaic (PV) generator models are summarised in Table 2, together with information on their cost, power output under Standard Test Conditions (STC), and projected 20-year lifespan. The $790 Kyocera Solar KC200, which costs $190 for the tower, produces 0.17 kW of power. With a $160 tower and a somewhat lower price of $729.02, the BP Solar SX 170B has a higher power output of 0.21 kW. With power levels ranging from 0.20 kW to 0.21 kW, Evergreen's three models—the Spruce ES-170, ES-180, and ES-190—have prices between $730.98 and $821. Finally, the cheapest module is Solar World's SW-165, which costs $710.02 and produces 0.20 kW with a $170 tower. With an anticipated 20-year lifespan, all models are appropriate for long-term hybrid energy systems.

4.6. Photovoltaic Power

In order to mimic the PV array's performance, the modeling procedure has taken into account the Maximum Power Point Tracking (MPPT) controller at any temperature of the PV modules. The output power of the PV panel may be predicted by this model at different temperatures and radiation levels.

5. CONCLUSION

This study's conclusion shows how efficient modelling and sizing optimisation of wind turbine (WT) and photovoltaic (PV) hybrid systems may greatly improve energy management and production. The research offers a thorough framework for assessing and enhancing system performance by combining sophisticated mathematical techniques such wind speed correction, Weibull distribution analysis, and Maximum Power Point Tracking (MPPT). The significance of choosing suitable technologies based on cost, efficiency, and lifetime is shown by the examination of several turbine and PV models. In the end, this strategy helps to make hybrid power systems economically viable, which makes them a desirable alternative for renewable energy solutions in addition to guaranteeing a dependable and sustainable energy supply.

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