



Performance Analysis of Hybridizing Solar and Wind Energy

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I. INTRODUCTION

Hybrid energy systems have received worldwide attention for remote locations where grid supply is not feasible [1]. In remote areas, various renewable energy technologies such as standalone solar systems and minigrids have been introduced to achieve an efficient energy supply [2]. However, many of them do not offer real versatility to the end user or are not practical when they are launched, usually due to the lack of sales to offset product replacement and operating and repair costs. Furthermore, in the light of global grid growth, the concern that grid arrival at a particular location will render off-grid systems useless has recently spread among energy system investors [2, 3]. Climate change has become a major environmental concern in recent years as Green House Gas (GHG) emissions have increased [4]. As a result, it has been urged to look for alternative energy sources that can produce electricity [4], and wind and solar energy have been proven to be effective in producing cost-effective electricity [4]. In older times, only solar energy was used for generating electricity. Using only solar energy systems is having some challenges. These systems are not capable of generating maximum power during cloudy or rainy days [5]. People who use this system will be without power until the battery has been discharged [5]. Maximum power can be produced by combining solar and wind energy production techniques [5]. For electric power generation systems, these kinds of integrated systems guarantee a pollution-free and accident-free inventory [5]. Various off-grid methodologies, such as hydroenergy and geothermal energy, have been tried in the past few years to improve power supply reliability, but they have failed [6, 7]. The key cause for such strategies' inability is their high energy prices, which are unaffordable on a broader scale [6, 7]. The system presented in this paper is based on various optimization techniques for enhancing the efficiency of the system, which can provide continuous power at lower costs, thus reducing the financial pressure on people living in rural areas. Integrating solar and wind energy into hybrid power generation systems will minimize induced power volatility relative to single Variable Renewable Energy (VRE) systems, increasing overall system efficiency and reliability [7]. As a result, the amount of capacity used in the device can be decreased significantly, resulting in significant cost savings [7]. The major contributions of the paper are as follows:

- (i) In this paper, a hybrid and effective system for harnessing power is suggested based on IoT and a combination of solar and wind energy
- (ii) The aim of this paper is to find the solution to the challenges in resolving carbon emission and enhancing power efficiency, along with the focus on predicting the cost of energy from the system

The remainder of the paper is organized as follows. The associated work is covered in Section 2. The importance of the research is explained in Section 3. The proposed architecture and optimization methods are explained in Section 4. Section 5 summarizes the research findings, and Section 6 concludes the paper. Section 7 explains the limitation of the current study and future scope of work.

II. RELATED WORK

Due to increased awareness regarding climate change and other environmental issues, the expectations for generating power from renewable sources of energy have increased [8]. Various studies have been conducted to suggest cost-effective and efficient systems for generating electricity. In [8], the authors have suggested a novel analysis technique for pumped storage and thermal power generator with a detailed introduction of renewable energy sources (RESs). For addressing operational planning for thermal power generators and output decisions for pumped storage, this paper uses Tabu search and interior point methods [9, 10]. The authors of [11] gave a high-level overview of the functional integration of hybrid renewable energy systems (HRES) in multienergy buildings. The paper discussed the most commonly used HRES solutions in the residential sector, as well as an investigation of HRES integration with thermal and electrical loads in residential apartments, which were then connected to external energy grids. The authors of [12] demonstrated the advantages of expanding the integration of renewable energy sources in the insular system. The main focus of this paper is on profit maximization, cost efficiency, GHG reduction, and time consumption in power generation. The authors of [13] submitted a review of different control strategies used by battery storage systems for smoothing the output power of wind turbines in order to improve future energy applications. The authors of [14] applied model predictive control to a three-phase inverter and used another model to estimate future system voltage forecasts for a given set of voltages. The method presented in this paper avoids the use of linear and nonlinear controllers by avoiding the use of a modulator, and it was found to be effective and simple to implement. The authors used an integrated approach in [15], combining spatially explicit resource potential analysis with high spatial resolution modeling of the US electricity system. Various wind supply curves, reflecting variations in siting regimes such as regulatory, physical, and social land-use factors, are analyzed in this study to determine the impact of potential wind growth. In [16], the authors have optimized a hybrid energy system for catamaran ship. The authors have discussed PV performance, generator performance, dual-input buck boost, and simulation. In [17], the authors have suggested an economic day-ahead scheduling technique for a sustainable cogeneration system. A dynamic programming model was developed for which the goal is to minimize fuel consumption. In [18], the authors have focused on the design and performance analysis of dual-axis tracking solar systems. The authors have also conducted a detailed review of various types of solar tracking systems and types of solar PV cells. The performance analysis for various solar PV systems suggested by other authors as per the literature reviewed is compared in Table 1. Recent development also focuses on developing efficient battery technology for energy storage in smart grid systems. In [26], the authors have developed a power management system, which is capable of controlling the power flow for an integrated system. However, using this technology as a storage system will make the overall system more expensive, which might not be affordable for low-income countries. We want to keep the system as simple as

possible through which we can cover both high-income and low-income countries. The authors of [27] have discussed finding an effective solution to replace natural gas for power generation with wind and solar energy. This study has also discussed the different cases of carbon-dioxide emission and the total cost of energy. However, the scope of the study is limited as in countries like Yemen and Saudi Arabia, natural gas is the most widely used for power generation, and it is not possible to extract the full potential of the integrated grid systems in these regions. So we have to develop a low-cost system to avoid wastage of investments in installing integrated systems under these conditions.

In [28], the authors have suggested a model for calculating tariffs at charging stations for electric vehicles. This paper also suggests the use of solar energy for charging electric vehicles (EVs). The approach suggested in this paper is unique, but various factors that affect the efficiency of the system such as tilt angle of the PV array have not been discussed. In [29], the authors have suggested a trigeneration system that produces ammonia, hydrogen, and electricity through the integrated solar system. This system can be fully implemented in high-income and middle-income countries, but in low-income countries, implementing this technique would be challenging as ammonia is a harmful substance and might cause respiratory diseases to the person who is operating the energy system or living nearby the system.

Upon analysis of the literature, we found that most of the works focus on developing complex systems which might affect the efficiency of the system and are not feasible for low-income or poor nations. Through this paper, we have tried to improve the system through various optimization techniques so that the system would be feasible for all.

III. SIGNIFICANCE OF WORK

In contrast to conventional fossil fuel-based resources, renewable energy sources play a critical role in maintaining the country's economy and quality of life [30]. Due to the increase in severe problems as a result of climate change, this research may be useful in addressing the issues to some extent. Using an integration of solar energy and wind energy will cause zero pollution, low greenhouse emissions, and fewer challenges related to waste management [31]. The system suggested in this paper is a better alternative for nuclear energy for fulfillment of 100% of electricity needs of the world [31]. The solution suggested in this paper will help in achieving a continuous power supply without the risk of harming nature or humans. Various studies have shown only a single renewable energy source for producing electricity, either solar energy or wind energy. Single renewable sources, on the other hand, become problematic in terms of operational costs and energy yield due to the intermittent nature of renewable sources [32]. Two or more renewable sources are combined to form a hybrid energy system (HES) based on these drawbacks [32]. The main aim of implementing such a system is to maximize power production, lower operating costs, and increase system productivity [32]. The hybrid system proposed in this paper can be quickly introduced to provide end users with highly efficient and reliable power. An HES may be used as a standalone system or as part of a grid [32]. Standalone systems, on the other hand, need a lot of storage to handle the load [32]. In grid-connected systems, the storage can be small, which can decrease the efficiency of the system. So, it is advised to use HES in standalone modes for generating high power. The energy produced from the suggested system is stable without causing any type of pollution.

With the current challenge of not having enough space to construct power plants as the world's population grows, it is critical to make efficient use of land used to produce electricity and to think carefully when constructing a power plant. The power plant must be located near the power availability area to avoid power transmission losses and low power transit costs [31]. Thus to increase the reliability of power generation, integrated systems are used. Furthermore, to increase the dependency of the overall system only on one technique, either solar/wind energy, the size of the storage battery is needed to be reduced and using integrated systems would help in achieving this.

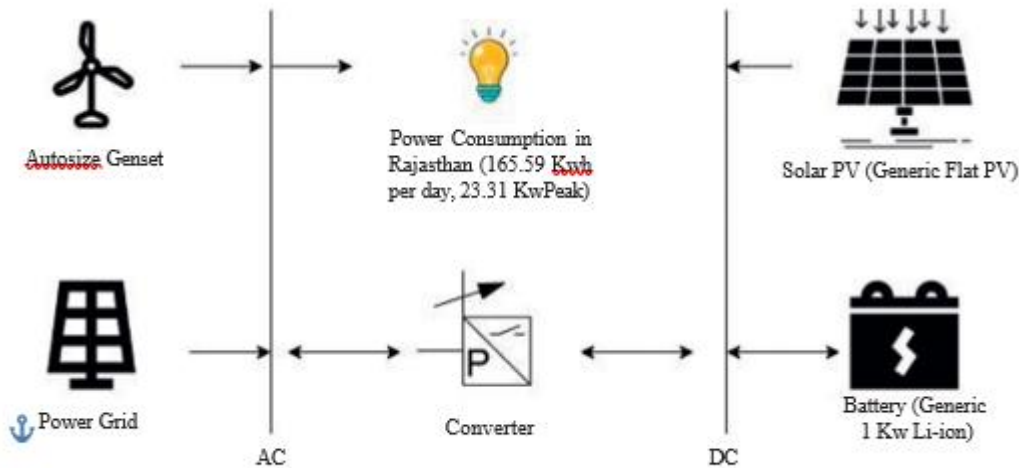


FIGURE 2: Grid system internal structure.

The software Hybrid Optimization of Multiple Energy Resources (HOMER) [46] was chosen for simulations and system design. We chose this software because it can perform essential tasks like optimization, simulation, and sensitivity analysis. After the users' data have been simulated, HOMER determines the best setup based on the lowest net present cost (NPC) [46]. Sensitivity analysis is carried out to ensure that only the best components are used in the system design. We chose the rural areas of Rajasthan, India, for system testing because the state is covered in desert, allowing ample solar energy to be harnessed. The community consumes 165.59 kWh per day, with a peak demand of 23.31 KW. The load profiles were created using public databases [47, 48] and a poll conducted by the Government of Rajasthan in India. The random variability from one day to the next is 10%, and the variability from one-time step to the next is 20%. Summer demand (May–July) was found to be moderate, and winter demand was found to be low (November–January). Electrical service can need a distribution system, whether the system is self-contained or connected to the grid [46]. A grid connection system would need an 11 KV/220V step-down transformer as well as an automatic transfer switch to resolve any power distribution anomalies. The seasonal load profile generated is shown in Figure 3.

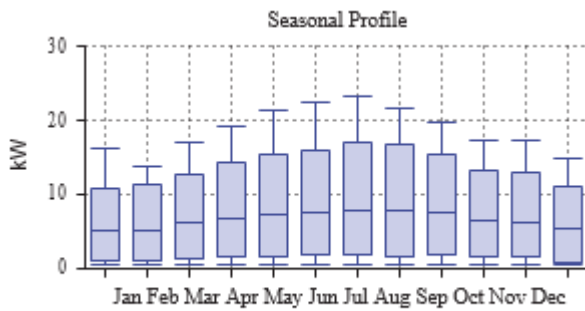


FIGURE 3: Season-based load profile obtained for the suggested installation location.

The components used for designing the system are explained in Tables 2–5, respectively.

The purpose of using the Autosize Genset generator is that this generator automatically adjusts itself according to the load. The capacity of the generator is small so that it cannot produce capacity shortages in cases of sensitivity and in the future if the multiyear analysis is used. This generator is also capable of adjusting its fuel curve to match its size (source: <http://www.homerenergy.com>).

Generic 10 kW wind turbine is used for our study. Table 3 lists the wind turbines’ various parameters, while Figure 4 depicts the power curve. The turbine’s predicted lifespan was discovered to be 20 years. Although the initial investment is low, replacement costs are high. However, when compared to high-quality wind turbines during the project’s lifetime, the HOMER simulation findings show that the turbine contributes to a less net present cost (NPC) due to its low capital cost [46]. The surface area criteria are based on National Renewable Energy Lab (NREL) standards [46]. According to NREL, the capacity per unit area is 3.0 ± 1.7 MW/km². Therefore, the area required for 10 kW wind turbine is 2500 m². The capacity of the wind turbines can be optimized by a genetic algorithm [49] given as Algorithms 1 and 2, respectively. Upon analysis of HOMER, we found that the lifetime of the overall system would be in the range of 20–30 years, which is a good sign.

TABLE 2: Generator specifications.

Type	Autosize Genset
Size (kW)	1.2 kW
Capital cost (INR)	500 INR
Restoration cost (INR)	500 INR
O&M cost (per operational hour)	0.030 INR

TABLE 3: Wind turbine specifications.

Type	Generic 10 kW
Hub height	24 meters
Capital cost (INR)	50000 INR
Restoration cost (INR)	50000 INR
O&M cost (per operational hour) lifetime	500 INR/year 20 years

Due to the seasonal nature of renewable energy sources, energy storage devices are necessary to ensure a constant supply of energy from renewable sources. We have considered the load following strategy [46] in developing our model. Due to the sudden increase or decrease in power supply, hybrid systems require additional reserves to tackle the challenges related to sudden increase or decrease. The operating reserve was considered as 10% of the hourly load as recommended by [46] for maximizing efficiency. The specifications for the solar PV and storage devices are given in Tables 4 and 5, respectively.

Simulations and Analysis. For the evaluation of the proposed system, various configurations such as grid-only systems, renewable energy sources (RES) systems, and Grid-RES hybrid systems are analyzed. The optimization results are recorded in Table 6.

TABLE 4: Storage battery specifications.

Type	Generic 1 kWh Li-ion
Lifetime	15 years
Capital cost	550 USD
Restoration cost	550 USD
O&M cost (per operational hour)	10 USD/year
Throughput	3000 kWh

TABLE 5: Solar PV specifications.

Type PV	Generic flat
Derating factor	80%
Capital cost	2500 USD
Restoration cost	2500 USD
O&M cost (per operational hour)	10 USD/year
Lifetime	25 years

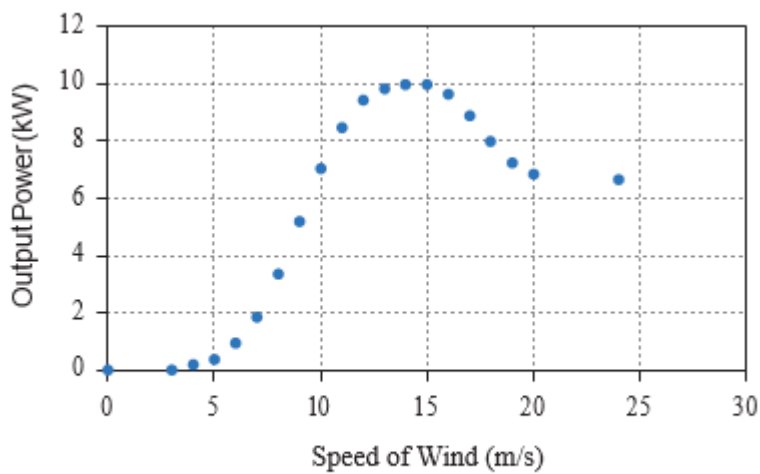


FIGURE 4: Scatter plot of the wind turbine in terms of power.

- (1) Initialize $GA \in [0,1]$, $POS \in f(V)$ //Particle swarm optimization, $f(V)$ ♦ Functional Decision
- (2) If - -
- (3) POS optimizes $w(f(n)) \in NIS//NIS$ ♦ noninferior solutions, $w(f(n))$ ♦ weighted single objective function
- (4) **Then**
- (5) Use Crowding Distance Method for the solutions Obtained in step 3
- (6) **If**
- (7) User submitted ♦ true, terminate the algorithm and Solutions ♦ accepted
- (8) **Else**
- (9) Values recorded
- (10) Evaluate Fitness for each individual, do Genetic Operations
- (11) Return Values recorded
- (12) Evaluate Fitness for each individual, do Genetic Operations
- (13) Return to Step 2

ALGORITHM 1: Optimization of the capacity of wind turbines.

- (1) Initialize $u \in 0 \text{ m/s}^2 \in POS$ in decision making variables// u ♦ initial velocity
- (2) Evaluate Fitness Values, Extreme Points
- (3) New u and position updated
- (4) **If**
- (5) Steps 1,2,3 ♦ True, conditions satisfied
- (6) Algorithm terminated
- (7) **Else**
- (8) Go to step 2 again

ALGORITHM 2: For noninferior solutions.

TABLE 6: RES configuration optimization result.

PV (kW)	Wind turbine	Battery	Conv (kW)	Initial capital	Operating cost (USD/Year)	Net NP C	Coe (\$/kWh)	Renewable factor	Capacity shortage
26	10	100	25	\$63,531	\$16,405	\$84,413	0.118	0.028	0.10
-----	11	120	25	\$77,762	\$21,375	\$83,201	0.156	0.028	0.10

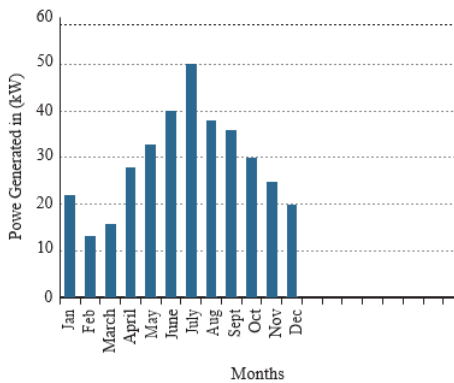


FIGURE 5: Monthly power production at 10% shortage.

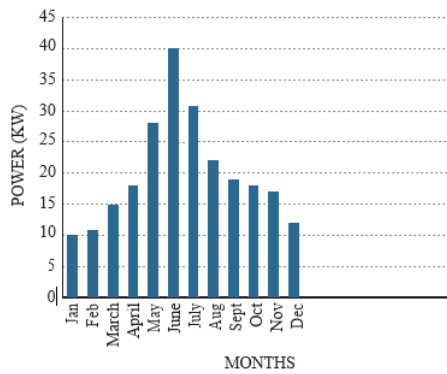


FIGURE 6: Monthly power production of Grid-RES system.

The HOMER findings show that the RES only setup is achievable with the available resources. This result was achieved after numerous trials, mistakes, and the removal of inefficient data in order to reduce simulation time.

This system is economically feasible at 10% shortage. The monthly production of power is shown in Figure 5. In Grid-RES systems, it has been found from HOMER simulations that these systems are feasible with currently available re- newable resources. This type of system is also economically efficient. Upon optimization, it has been found that the system gives a net present cost (NPC) of \$3,45,198. The renewable factor for this type of configuration is 77.6%. In this type of configuration, battery and inverter are not necessary as the grid network acts as a backup for the system. The monthly power production is given in Figure 6.

Sensitivity Analysis. The control parameters of a system can be varied in sensitivity analysis to examine the effect of these parameters on the system’s effectiveness [46]. This aids the designer in creating a system that is effective. A sensi- tivity analysis is often performed to ensure that the system is reliable. Because the aim is to protect 100 percent of the load, the energy system would be expensive. A sensitivity analysis of the capacity constraints for the system will provide the details about how much amount is to be paid by the cus- tomers for more effective system in terms of hours of re- liability. Values from 0 to 15% with a phase of 2% were given as capacity constraints inputs. In addition, a sensitivity analysis was carried out to research the conditions under which the available findings are true for PV modules and battery prices and how much the cost of the device would differ with the variance of these prices. A sensitivity analysis was performed to evaluate all possible scenarios between these rates, where capital cost multipliers of 1.5 to 3.5 were given for the solar PV capital cost, and multipliers of 1 to 2 were given for the battery capital cost. For running the simulations, the time step was set to 40 minutes (instead of the default 60 minutes in HOMER) to effectively adjust the load and output of electricity. The maximum number of simulations per optimization was set to 25,000. This implies that simulations would be discarded if they have not been completed until the value has been achieved. Increasing this value therefore dramatically increases the simulation time. The device design accuracy and the NPC accuracy were

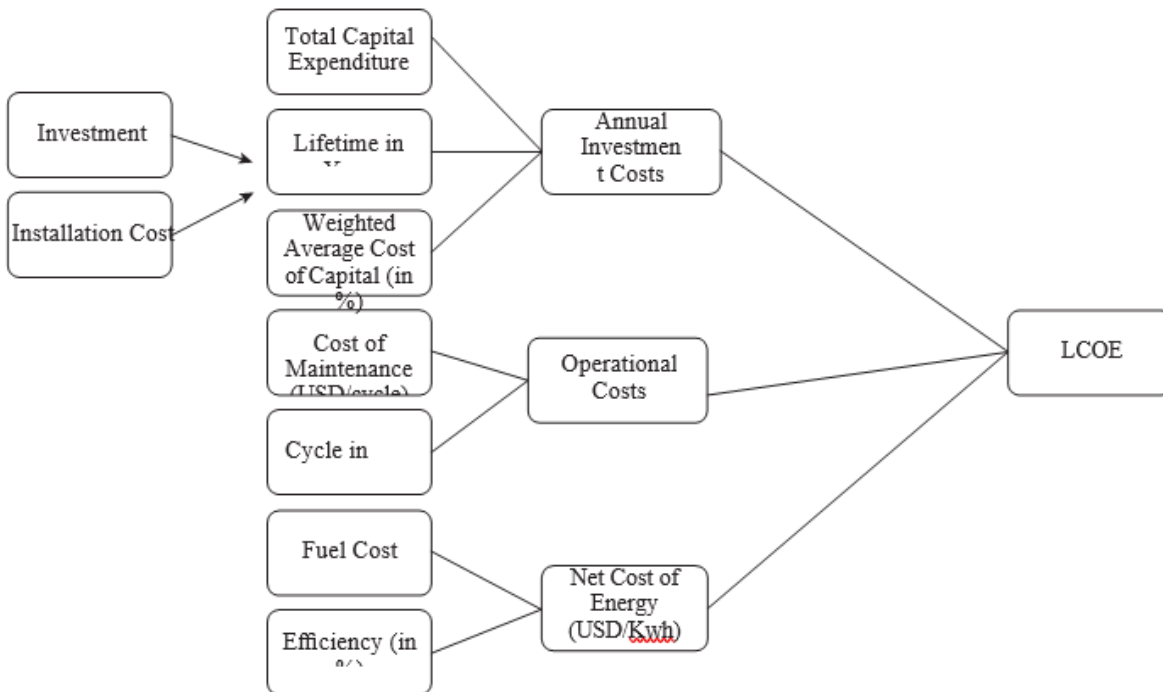


FIGURE 7: Flowchart for calculation of LCOE.

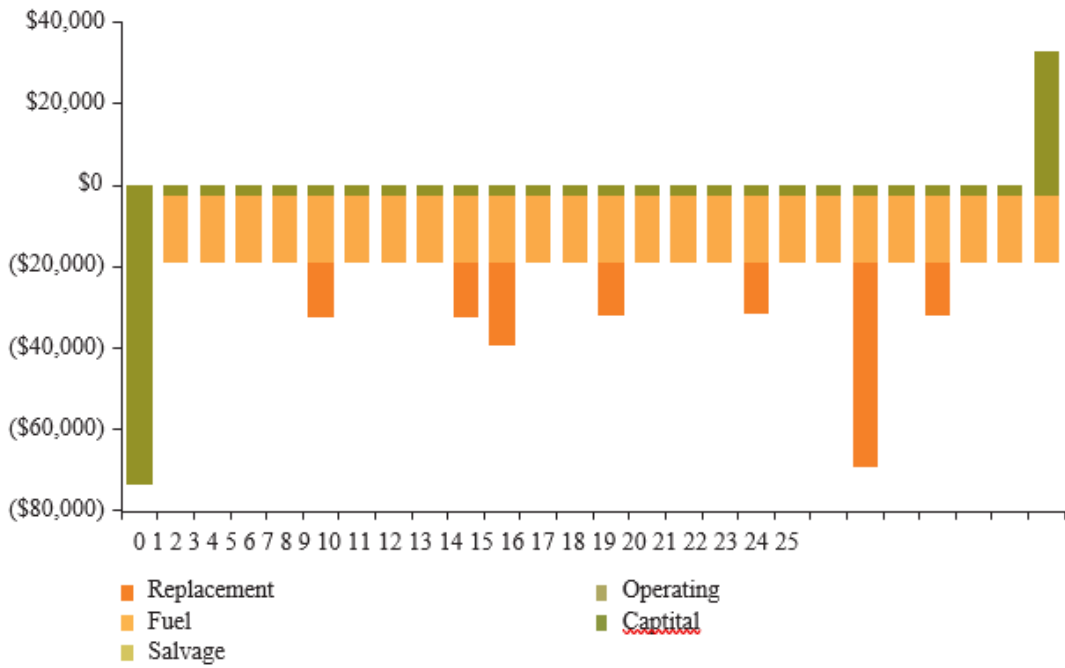


FIGURE 8: Cash flow diagram showing the cost efficiency of the suggested system.

TABLE 7: Cost analysis between various systems.

System configuration	PV array number	Number of wind generators	Battery quantity	PV converter	Cost (in USD)
Single PV	50	0	10	15	\$66,000
Single wind	0	10	5	0	\$56,650
Nonoptimized	20	5	6	8	\$56,300
Suggested system	15	6	6	6	\$49,500

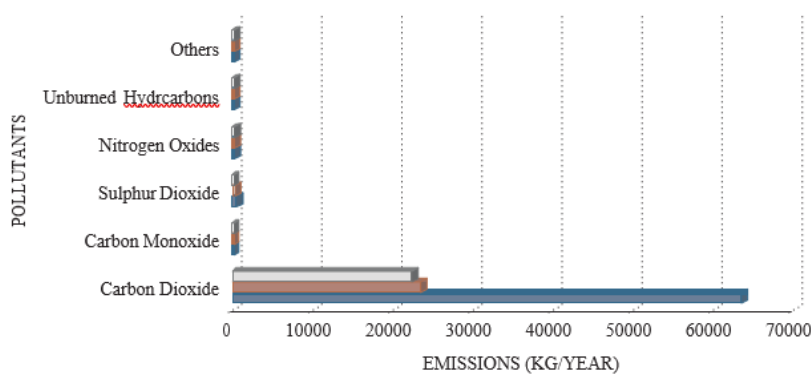


FIGURE 9: Comparison between greenhouse emissions of various systems. Blue bar indicates a grid-only system, orange bar indicates grid- wind system, and grey bar indicates grid-wind-PV system, which is suggested. defined by maximum simulation errors set at 1% and 2%, respectively.

The efficiency of the system is shown in Figure 7, Figure 8, Table 7, and Figure 9, respectively, with a comparison between various systems in terms of cost analysis and greenhouse emissions. The flowchart for the calculation of LCOE (levelized cost of heat) [50] is given in Figure 7.

Clearly, we can see from Figure 8 that the system suggested in this paper is efficient. It can also be seen that the optimized PV system is more cost-effective than other systems. It can also be inferred from the results that most of the energy is supplied by wind.

IV. CONCLUSION

Due to the growth of population and environmental pollution, the demand for efficient production of electricity has increased. Utilizing solar and wind energy for electricity production will help in resolving the challenges such as climate change and greenhouse emissions and can emerge as the best solution for resolving the energy crisis. The hybrid energy system suggested in this paper has advantages such as continuity in power supply, high efficiency, low maintenance cost, optimized utilization of the resources, and load management. The results given in this paper show that the use of hybrid PV-wind power generation units could save up to 10%–20% of the cost of current systems. This study encourages the use of hybrid systems in India and abroad in order to improve electricity production sustainability. Hybrid systems will provide a viable, secure power supply to rural areas while also providing a pool of funding for community grid maintenance and economic development. Ultimately, these systems will help to increase the usage of renewable energy for generating electricity globally and thereby contribute to resolving the environmental problems currently facing the world.

V. LIMITATIONS AND FUTURE SCOPE OF THE WORK

Solar energy and wind energy undoubtedly come to people's mind when we talk about renewable energy. In an hour, the sun emits enough energy, which can cover human needs for a year.

This property makes solar energy the best form of energy to be integrated with other energy forms. However, with the current technology, we are unable to extract the full potential of the integrated systems. Some amount of energy gets wasted due to inefficient operation. According to recent reports [51], it has been shown that the PV panels have a median degradation rate of 0.5% per year. It may be high in hot climate areas and rooftop systems. The degradation rate of 0.5% shows that the energy production from solar PV will decrease at the rate of 0.5% per year. This will make the system inefficient over time. Furthermore, the unpredictability and intermittency of solar energy make the solar PV panel less reliable. Solar panels require additional inverters to convert DC to AC energy in order to be used on the power network, which makes the system complex and increases the installation time and circuit development costs. For a continuous supply of electricity on grid connections, PV panels also require storage batteries along with inverters, which also increases the investment costs. Moreover, the installation of solar PV panels usually requires a large area of land for a period of more than 20 years. Also, solar PV is fragile and can be damaged easily, so insurance costs also increase the overall costs of the systems. Our future work will be based on resolving these challenges and the development of microenergy grids with micro-PV cells, which would require less complexity and installation area. This system will be further integrated with blockchain technology to increase the efficiency of the system.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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