

# Performance Analysis and Efficiency Enhancement of Hybrid Solar Energy Systems in Lucknow, India

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## Abstract

Power shortages and frequent load shedding remain common challenges in many developing countries, forcing households and institutions to rely heavily on diesel generators for backup electricity. Similar energy reliability issues are observed in Lucknow, India, where interruptions in grid supply affect residential, commercial, and institutional operations. To address this problem, a hybrid renewable energy system has been proposed with the objective of improving energy reliability while minimizing the Net Present Cost (NPC) over the project lifetime.

In this study, HOMER software was utilized to model and optimize a grid-connected hybrid renewable energy system integrating solar photovoltaic (PV) and wind energy resources. The optimized configuration consists of 36 kW solar PV capacity, 90 kW wind turbines, and a 12 kW power converter. Simulation results indicate that the proposed hybrid system significantly enhances overall system performance. The hybrid configuration achieved approximately 69.17% higher efficiency compared to a solar-only system and about 144.6% higher efficiency than a wind-only system.

A techno-economic analysis conducted for a 25-year operational period demonstrates notable financial benefits. The hybrid system is estimated to reduce annual energy expenditure by nearly ₹6,28,970, indicating strong economic feasibility. The results are consistent with earlier studies on hybrid renewable energy optimization using HOMER software, including research conducted by Linta Khalila and A. Khan Faizan, which emphasize the techno-economic advantages of solar-wind hybrid systems.

Considering the favorable solar radiation levels and seasonal wind potential in the Lucknow region, the proposed hybrid renewable energy system offers a promising and sustainable solution for improving energy reliability while reducing dependence on fossil-fuel-based backup generation.

**Keywords:** Hybrid Renewable Energy System, Solar Energy, Wind Energy, HOMER Software, Cost-Effectiveness, Energy Optimization.

## 1. Introduction

Rapid depletion of conventional fossil fuel resources along with increasing environmental concerns has led to a growing global interest in renewable energy technologies. Countries around the world are gradually shifting towards sustainable energy sources in order to reduce greenhouse gas emissions and ensure long-term energy security. Among the various renewable

options, solar and wind energy have emerged as two of the most promising alternatives due to their widespread availability and clean nature. However, when used individually, these resources often suffer from intermittency and variability caused by changing weather conditions.

To overcome these limitations, hybrid renewable energy systems have been developed by integrating multiple renewable sources within a single system. A combination of solar photovoltaic and wind energy is particularly advantageous because the availability patterns of these resources often complement each other. Hybrid systems improve overall energy efficiency, enhance system reliability, and reduce operational costs. They also provide environmental benefits by minimizing dependence on fossil-fuel-based electricity generation. Such integrated systems are increasingly being adopted in both grid-connected and remote power applications to ensure a more stable and sustainable electricity supply.

Designing and evaluating hybrid renewable systems requires advanced modelling and optimisation tools. One widely used software platform for this purpose is HOMER (Hybrid Optimization Model for Electric Renewables). This software allows researchers to simulate and optimise different configurations of renewable energy systems by analysing parameters such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), capital investment, and operational expenses. HOMER evaluates multiple combinations of system components including solar panels, wind turbines, converters, and energy storage devices to identify the most cost-effective and technically efficient configuration for a specific geographic location. Several previous studies have successfully applied HOMER to examine the feasibility and economic performance of hybrid renewable systems under varying climatic conditions and load demands (Lambert et al., 2006; Ngan and Tan, 2012; Sen and Bhattacharyya, 2014).

Recent advancements in hybrid energy technologies have enabled the integration of multiple renewable resources such as solar, wind, biomass, and small hydro systems in different operational arrangements. These integrated systems improve energy reliability and help address challenges related to grid limitations and weather-dependent energy production. Hybrid systems are particularly beneficial for regions with unreliable electricity supply or rapidly increasing power demand, and they play a vital role in achieving sustainable and environmentally friendly energy solutions (Kapoor et al., 2017; Rehman and Al-Hadhrani, 2010; Bhattacharjee and Dey, 2014).

In the present research, the feasibility of a grid-connected solar–wind hybrid energy system without battery storage has been examined for the city of Lucknow, India. The study evaluates the performance and economic viability of integrating wind energy with solar power using HOMER simulation tools. The results indicate that incorporating wind turbines into the system significantly improves system reliability and reduces the overall cost of energy generation, making hybrid renewable energy systems a promising solution for the regional energy scenario.

## **2. Mathematical Modelling**

The hybrid renewable energy model proposed in this study has been developed using the HOMER (Hybrid Optimization Model for Electric Renewables) simulation platform. The configuration of the system is established based on regional data including solar radiation levels, electricity demand patterns, and available renewable energy resources in the study area. During the modelling process, different system combinations are simulated to determine the most suitable configuration in terms of technical performance and economic feasibility. The

optimization process evaluates parameters such as system capacity, component characteristics, and operational control strategies with the aim of improving system efficiency and minimizing total project cost. Sensitivity analysis is also carried out in order to examine how variations in key parameters such as solar radiation, wind speed, and load demand influence overall system performance. The best-performing configurations are selected based on predefined techno-economic criteria and their feasibility is further examined in detail (Lambert et al., 2006; Ngan and Tan, 2012; Rehman and Al-Hadhrami, 2010; Sen and Bhattacharyya, 2014).

The study area selected for analysis is Lucknow city in Uttar Pradesh, India, located approximately at geographical coordinates **26°50.8' N latitude and 80°56.8' E longitude**. The region experiences a humid subtropical climatic condition characterized by mild winters and extremely hot summers. The winter season generally occurs from late November to February, while the summer season extends from March to June with temperatures frequently reaching between **40°C and 45°C**. These climatic characteristics make the region highly suitable for solar energy utilization. In addition, the **National Institute of Wind Energy (NIWE), Government of India**, has reported that wind energy potential in the region can reach approximately **138 MW at 50 m hub height and around 1,260 MW at 80 m hub height**, indicating the possibility of integrating wind turbines with solar systems to form hybrid renewable energy configurations (NIWE, 2022; CEA, 2023).

Electricity demand in Uttar Pradesh has been increasing rapidly over the past decade. According to the **Central Electricity Authority (CEA)**, the peak power requirement in the state is expected to reach **31,917 MW during 2024–25**, which is very close to the demand levels observed in Maharashtra, the state with the highest electricity consumption in India. This growing demand places significant pressure on the state electricity distribution company, **Uttar Pradesh Power Corporation Limited (UPPCL)**, which already faces challenges related to supply reliability and infrastructure limitations. Such projections highlight the need for integrating renewable and decentralized power generation systems in order to reduce stress on the conventional grid network and avoid possible electricity shortages in the future (CEA, 2023; MNRE, 2022; Kumar et al., 2019).

Meteorological data used in the simulation indicates that the **maximum average solar radiation of about 6.570 kWh/m<sup>2</sup>/day occurs during the month of May**, while the **minimum value of around 3.600 kWh/m<sup>2</sup>/day is recorded in December**. Wind resource assessment also shows seasonal variation where the **highest average wind speed of approximately 5.370 m/s occurs in March**, whereas the **lowest value of around 3.040 m/s is observed during November**. These variations confirm the advantage of combining solar and wind resources within a hybrid energy system to balance seasonal fluctuations in renewable energy availability (Khalila, 2020; Faizan, 2021; Bhattacharjee and Dey, 2014).

For system modelling, a generic **flat-plate photovoltaic (PV) system with an installed capacity of 36 kW** has been selected as the primary solar component. The electrical output of the PV system can be expressed mathematically using the following relationship:

$$P_S = I_n(t) \times A_S \times E f f_{pv} \quad (1)$$

The efficiency of the photovoltaic module is determined using:

$$E_f f_{pv} = H \times PR \quad (2)$$

where  $P_S$  represents the electrical power generated by solar panels,  $I_n(t)$  denotes the solar irradiation at time  $t$  (kW/m<sup>2</sup>),  $A_S$  represents the panel surface area,  $E_f f_{pv}$  indicates the photovoltaic efficiency,  $H$  is the average solar radiation received on the panel surface annually, and  $PR$  denotes the performance ratio of the PV system.

The optimized hybrid configuration also includes a **G1 wind turbine with a rated capacity of 90 kW**. The theoretical power generated by a wind turbine can be estimated using the equation:

$$P_W = \frac{1}{2} \rho A_W V^3 \quad (3)$$

where  $P_W$  represents wind turbine power output,  $\rho$  is air density,  $A_W$  denotes the rotor swept area, and  $V$  represents wind speed.

The total electrical power produced by the solar–wind hybrid system is the combined contribution of both energy sources and can be represented as:

$$P_T = N_W P_W + N_S P_S \quad (4)$$

where  $P_T$  represents total system power generation,  $N_W$  is the number of wind turbines installed, and  $N_S$  denotes the number of solar panels in the system.

A **bi-directional power converter** is incorporated into the model to regulate power exchange between the DC and AC buses of the system. This component performs both rectification (AC to DC) and inversion (DC to AC) processes with an assumed efficiency of **approximately 95%**, enabling stable system operation and effective integration with the grid network. The economic evaluation of the system also considers a simplified tariff structure consisting of electricity charges in **Indian Rupees per kWh** along with fixed monthly charges.

The techno-economic evaluation of the hybrid system follows the methodology adopted in earlier studies related to hybrid renewable energy optimization (Khalila, 2020; Faizan, 2021; Rehman and Al-Hadhrami, 2010; Bhattacharyya, 2014). The **Net Present Cost (NPC)** represents the total life-cycle cost of the system and is calculated by combining capital investment, replacement costs, and present value of operation and maintenance expenses over the project lifetime. It is mathematically expressed as:

$$NPC = \frac{\text{Total Annualized Cost}}{\text{Capital Recovery Factor}} \quad (5)$$

The **real annual interest rate**  $I_{yI\_yI}$  is calculated using the nominal interest rate  $I_{nI\_nI}$  and the inflation rate  $f$ :

$$I_y = \frac{I_n - f}{1 + f} \quad (6)$$

The **Capital Recovery Factor (CRF)** is determined using:

$$CRF = \frac{I_y(1 + I_y)^k}{(1 + I_y)^k - 1} \quad (7)$$

where  $k$  represents the project lifetime.

The **Cost of Energy (COE)** represents the average unit cost of electricity produced over the system lifetime and is calculated as:

$$COE = \frac{\text{Total Annualized Cost}}{E_t} \quad (8)$$

where  $E_t$  represents the total annual electricity consumption.

The **Life Cycle Emission (LCE)** of the system, representing annual equivalent CO<sub>2</sub> emissions, is estimated using:

$$LCE = \sum_{i=1} \delta_i E_m \quad (9)$$

Finally, the **Renewable Penetration (RP)**, which indicates the share of renewable energy contribution in the total energy supply, is calculated using:

$$\%RP = \left( 1 - \frac{\sum E_c}{\sum E_r} \right) \times 100 \quad (10)$$

where  $E_c$  represents conventional energy contribution and  $E_r$  represents renewable energy production.

The overall configuration and operational structure of the proposed hybrid renewable energy system are illustrated in **Figure 1**, which represents the integration of solar photovoltaic arrays, wind turbines, converter units, and grid interaction within the optimized system architecture before optimization.

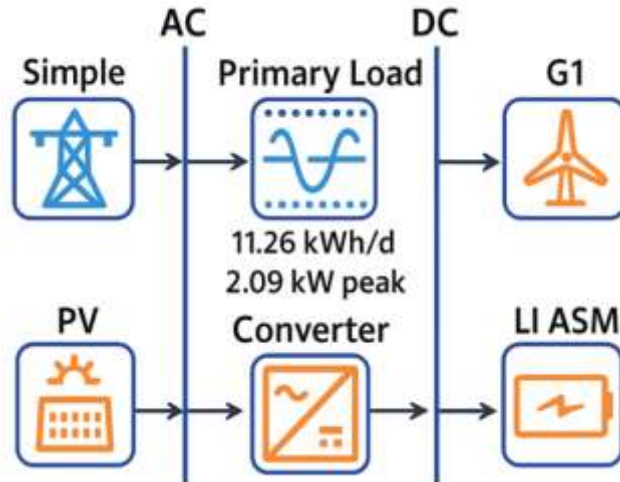


Fig. 1 System Architecture Before Optimization

### 3. Optimization and Outcomes

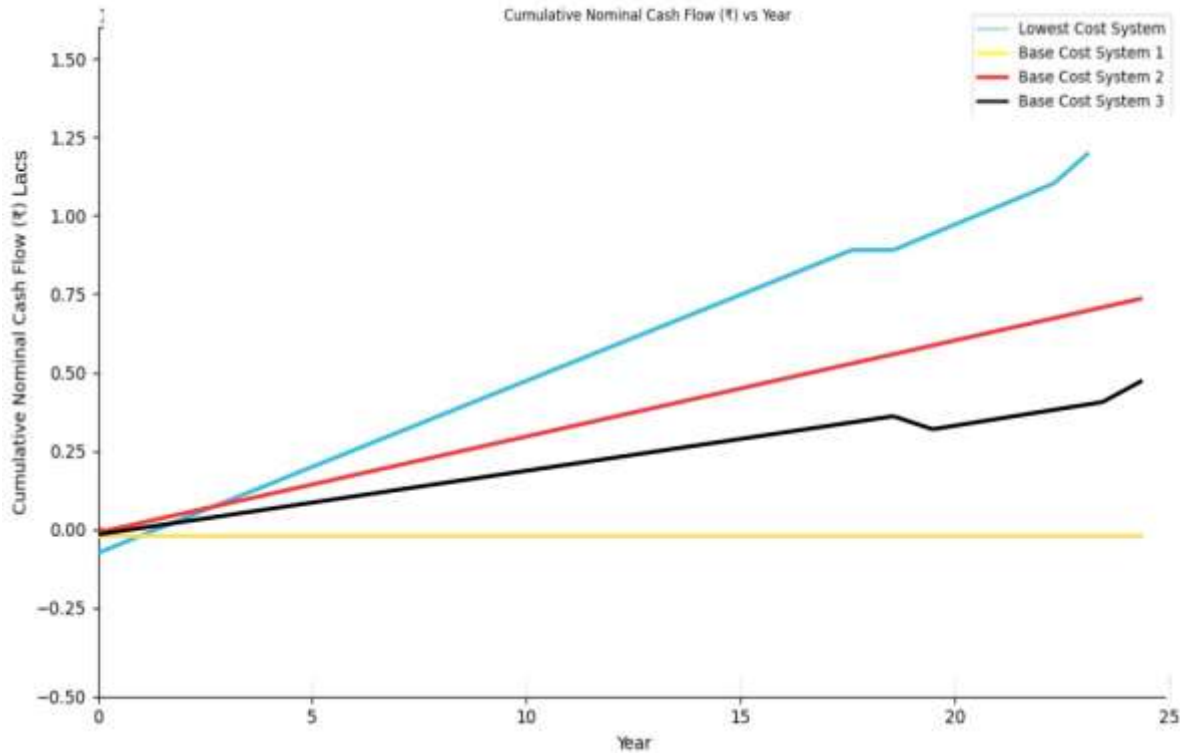
- A 36 kW generic PV plant, when simulated, is estimated to **produce 57,194 kWh per year**, achieving an **LCOE of \$0.119/kWh** and a 90 kW wind turbine, as per simulation results, is expected to **produce 89,204 kWh of electricity per year**.
- Table-1, shows the Simulation Report of Total Electrical Energy Production and Renewable Fraction and Max. Renewable Penetration.

Table-1: Simulation Report

Total Electrical Energy Production			Renewable Fraction and Max. Renewable Penetration	
Parameter	Production(kWh/year)	Production (%)	Quantity	Value (%)
Generic Flat Plate PV(36KW)	57,194	38.9	Renewable Fraction	99.4
Generic Wind Turbine(90KW)	89,203	60.7	Max. Renewable Penetration	1,46,534
Grid Purchases	588	0.400	-	-
Total	1,46,985	100	-	-

### 4. Results and Discussion

The study presents the outcomes of the simulations and subsequent analyses, evaluating multiple system configurations to assess their respective performance advantages and limitations. This comparative assessment supports the identification of the optimal design strategy for hybrid solar power systems in Lucknow, as detailed in the following sections.



**Fig. 2 Comparison between Base Cost System 1,2 & 3 and Lowest Cost System**

- **Base Cost System-1 v/s Lowest Cost System**

In Fig. 2 Base Cost System-1 uses Simple Tariff where as Lowest Cost System uses Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW. Simulation result shows that the hybrid cost system (lowest cost system) i.e., Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW, saves money Rs.6,28,970 per year and over the project lifetime 25 years Rs.1,57,24, 250. Thus, the hybrid system (Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW), is more efficient than the base cost system.

- **Base Cost System-2 v/s Lowest Cost System**

In the Fig. 2 Base Cost system-2 uses Generic Flat Plate PV 36.0 kw whereas lowest cost system uses Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW. Simulation result shows that Base cost system (uses Generic flat plate PV) saves Rs.3,71,758 per year and total saving in life time of 25 years would be Rs. 92,93,950 and hybrid cost system (lowest cost system) i.e., Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW, saves money Rs.6,28,970 per year and over the project lifetime 25 years Rs. 1,57,24,250. Thus, the hybrid system (Generic Flat Plate PV 36.0 kW, Generic wind turbine 90kW and system converter 12.0kW), is 69.17% efficient than the base cost system (Generic flat plate PV).

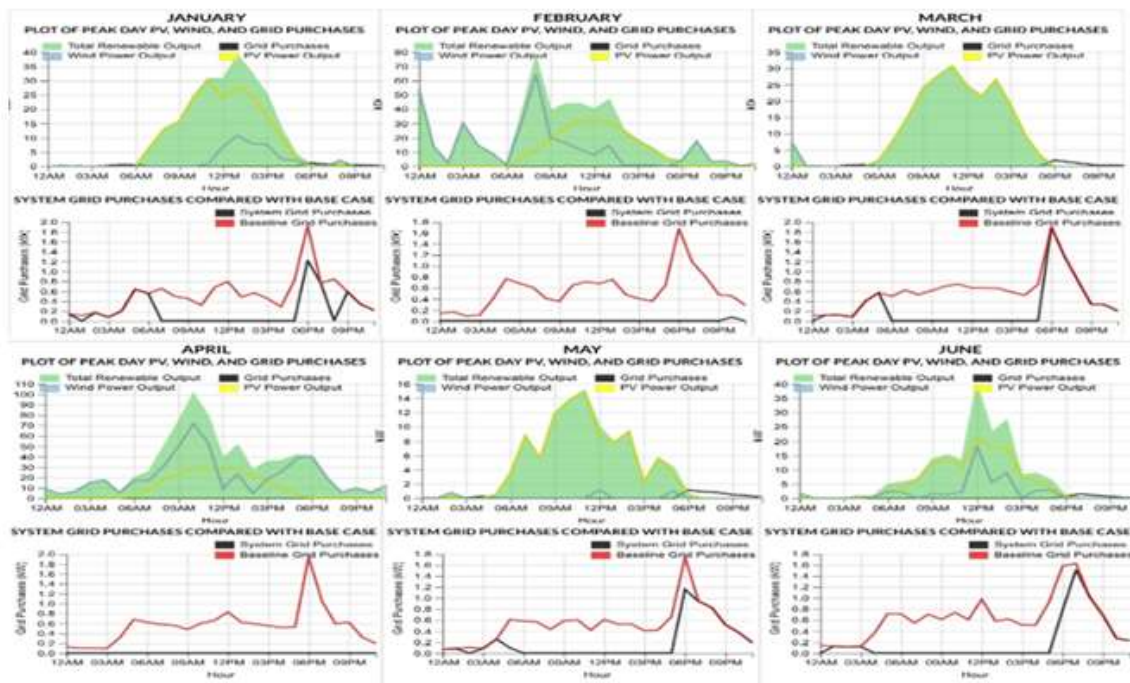
- **Base Cost System-3 v/s Lowest Cost System**

In the Fig.2 Base Cost system-3 uses Generic wind turbine 90 kW and system converter 12.0 kW whereas lowest cost system uses Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW. Simulation result shows that Base cost system (uses Generic wind turbine 90 kW and system converter 12.0 kW) saves Rs.2,57,212 per year and total saving in life time of 25 years would be Rs. 64,30,300 and hybrid cost system (lowest cost system) i.e., Generic Flat Plate PV 36.0 kW, Generic wind turbine 90 kW and system converter 12.0 kW, saves money Rs.6,28,970 per year and over the project lifetime 25 years Rs. 1,57,24,250. Thus, the hybrid system (Generic Flat Plate PV 36.0 kW, Generic wind turbine 90Kw and system converter 12.0kW), is 144.6% efficient than the base cost system (Generic wind turbine 90 kW and system converter 12.0 kW).

## 5. Conclusion

1. **Cost-Effectiveness of Hybrid Systems:** A hybrid solar and wind energy system, analysed using HOMER software, is more cost-effective and efficient than single-source systems. The hybrid system showed a 69.17% higher efficiency compared to a system that relies solely on solar PV, and a 144.6% higher efficiency compared to a wind-only system.
2. **Long-Term Financial Benefits:** Hybrid systems offer significant cost savings of Rs.1,57,24,250 over 25 years, reducing reliance on fossil fuels.

Lowest cost Hybrid Solar Power Generation is produced by Integrated Generic Flat Plate PV & Wind Turbine with system converter. Performance summary generated by simulation software for lowest cost system is shown in fig. 3. It will certainly change economy of the residents as well UP State, India if such studies are made for every district of the UP State and India on wider scale adaptation.



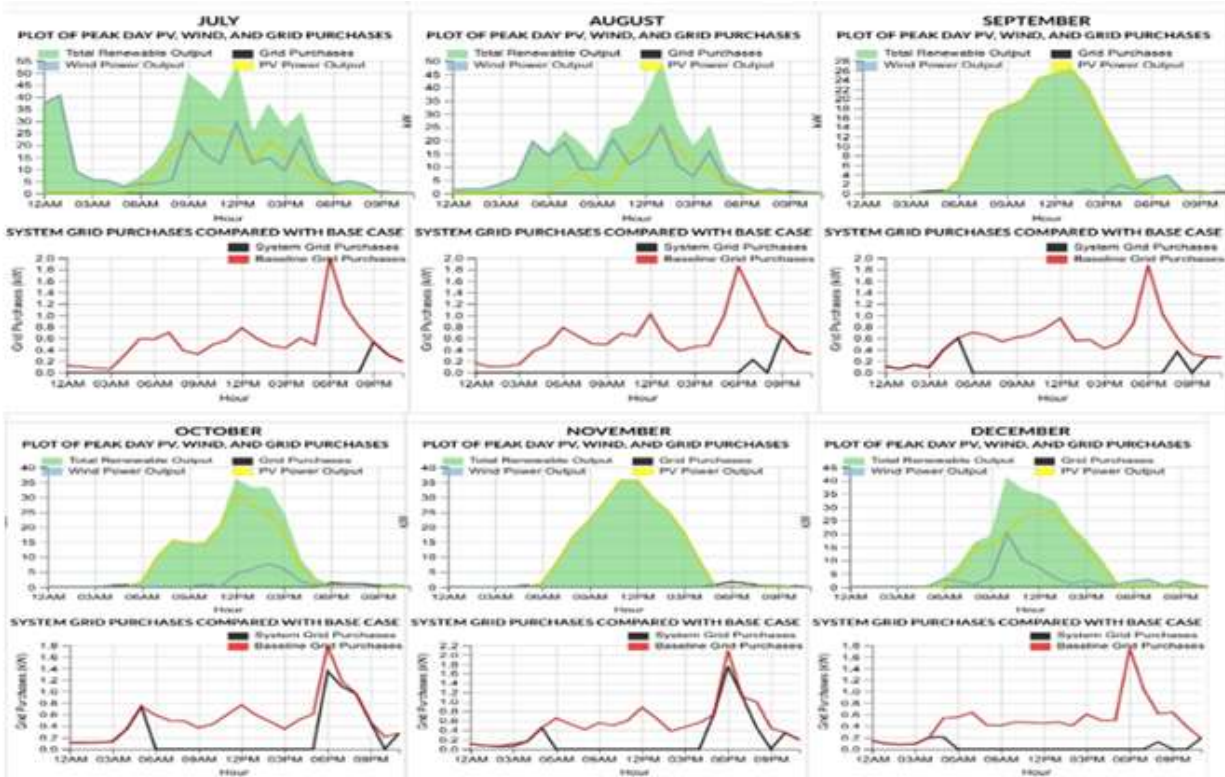


Fig. 3 Performance summary for lowest cost system

## Declaration

### Availability of Data and Materials

All data generated or analyzed during the present study are included in this manuscript. Additional datasets used in the modelling process (solar irradiance, wind speed, tariff data and HOMER simulation outputs) are available from the corresponding author upon reasonable request.

### Competing Interests

The authors declare that they have **no competing or conflicting interests** related to the publication of this research work.

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### Authors' Contributions

#### Garima Singh:

- Collected solar, wind, and energy demand data for the Lucknow region.
- Performed statistical analysis of the hybrid energy system.
- Conducted modelling and simulation using HOMER software.

#### Bharat Raj Singh:

- Guided system design, structure, and integration of solar-wind modelling.
- Performed optimization assessment and contributed to interpretation of outcomes.
- Provided overall supervision and contributed to the preparation and finalization of the manuscript.

Both authors contributed equally in drafting, revising, and approving the final version of the manuscript.

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