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Economic Viability of Grid-Integrated Hybrid Power Systems for Rural Areas in the Indo-Pak Border Region

Rahul Mishra[1 *], **Devendra Kumar Doda**[2]
[1,2]Department of Electrical Engineering, Vivekananda Global University, Jagatpura, Jaipur, India.
Email: mishra.rahul@vgu.ac.in[1], rahulmishra24@ gmail.com[2]

Abstract:
This study assesses the economic feasibility of a grid-connected hybrid power system (PV/Wind turbine) for rural applications in the Anupgarh region, Rajasthan, situated at 29.55° N latitude and 73.38° E longitude, near the IndoPak border. The analysis involves evaluating the potential of wind and solar energy by collecting data from various sources. The Hybrid Optimization Model for Electric Renewable (HOMER) software is utilized to analyze the data and determine the economic viability of the proposed system. Two models—off-grid and on-grid—are designed and optimized for comparison. Additionally, a sensitivity analysis is conducted to examine the impact of variations in grid energy costs on the overall system cost. Simulation results indicate that the proposed grid-connected hybrid system is the most cost-effective and suitable solution for the targeted region.
Keywords: *Grid-connected, hybrid power system, renewable energy, economic feasibility, HOMER, rural applications.*

I. INTRODUCTION

Renewable energy sources (RES) provide an effective solution to global warming and rising fuel costs. As a result, interest in RES, particularly photovoltaic (PV) and wind energy, has increased significantly [1], [2].

Hybrid power systems incorporating renewable energy are gaining popularity due to their numerous benefits
[3].

Despite the advantages of wind and solar energy, standalone solar or wind systems cannot ensure a continuous power supply due to their intermittent nature [4]. Since energy demand fluctuates over time, variations in solar and wind energy generation do not always align with consumer demand patterns [5]. Therefore, additional energy storage, such as batteries, is required to provide an uninterrupted power supply. Studies indicate that a hybrid PV/Wind/battery system is a reliable electricity source [6], [7], [8]. However, the high cost of battery storage makes standalone systems expensive [9]. Hence, finding a cost-effective alternative is crucial. When properly planned, a grid-connected hybrid power system can reduce storage requirements, lowering overall costs.

This paper aims to evaluate the economic feasibility of a grid-connected hybrid (PV/Wind turbine) power system for meeting energy demands in a specific region. For comparison, an off-grid hybrid (PV/Wind/battery) system is also designed. The paper is structured as follows: Section II provides an overview of the system model, Section III explains the methodology, Section IV presents the simulation models, and Section V discusses the optimization results. Finally, conclusions are drawn in Section VI.

II. SYSTEM DESCRIPTION

This study designs and analyses both grid-connected and off-grid hybrid power systems using HOMER software to determine the cost-effectiveness of different configurations. HOMER requires specific input data to optimize system performance, which is detailed in the next section [10]. **A. Load Profile**

The selected region experiences peak energy demand primarily due to irrigation pumps. The average daily energy consumption in the proposed area is estimated at 654.73 kWh. Figure 1 illustrates the daily load profile, showing peak demand between 17:00 and 23:00 hours, which influences system sizing. The peak load is considered to be 101.32 kW, with an assumed scaled annual average energy consumption of 654.73 kWh/day. Figure 2 presents the monthly average load profile for the region.

B. Wind Speed and Solar Radiation

Wind speed and solar radiation data for the Anupgarh region, Rajasthan (29.55° N latitude, 73.38° E longitude), near the Indo-Pak border, were obtained from the NASA Surface Meteorology and Solar Energy database. Wind speed data at 50 m above sea level for this location shows a range between 2.64 and 4.33 m/s, with the highest speeds occurring in June.

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Figure 3 illustrates the wind speed variations, while Figure 4 presents the monthly average solar radiation data. The annual average solar radiation for this region is estimated to be 4.56 kWh/m²/day, based on HOMER software inputs.

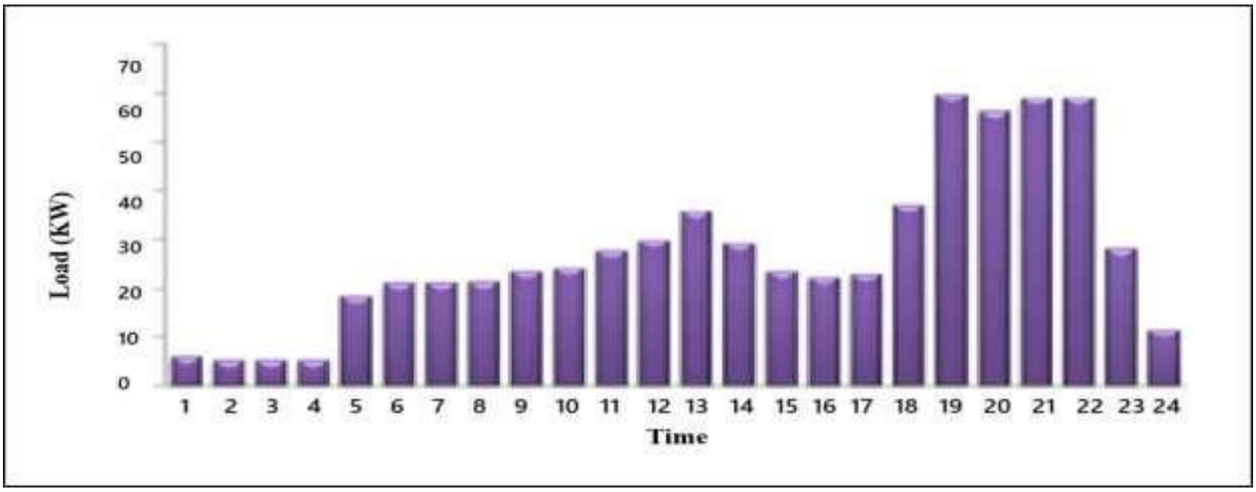

Fig.1. Load profile (daily).

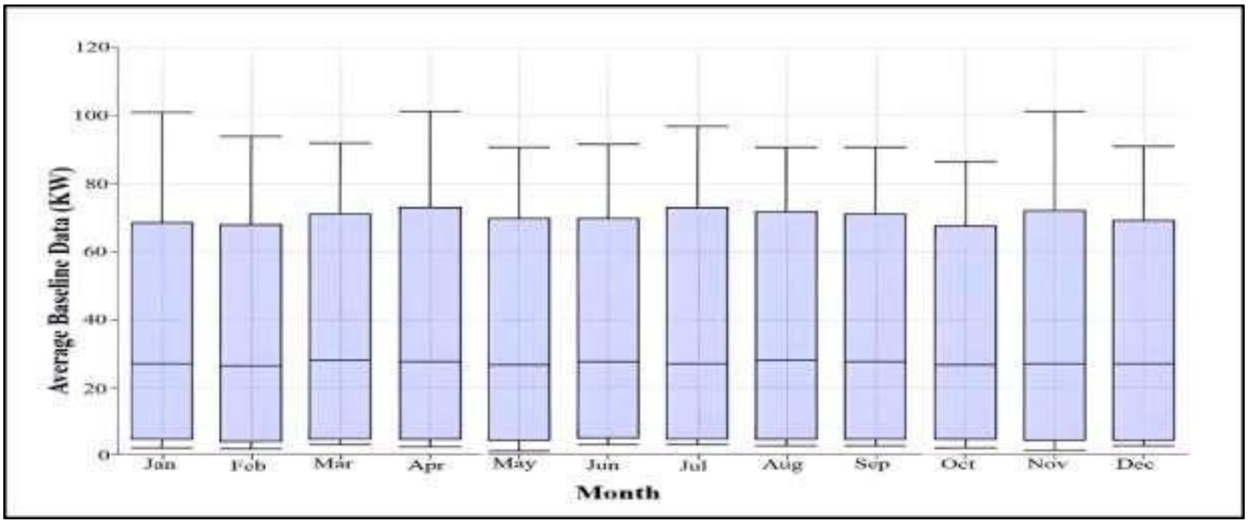

Fig. 2. Load for a complete year (monthly average).

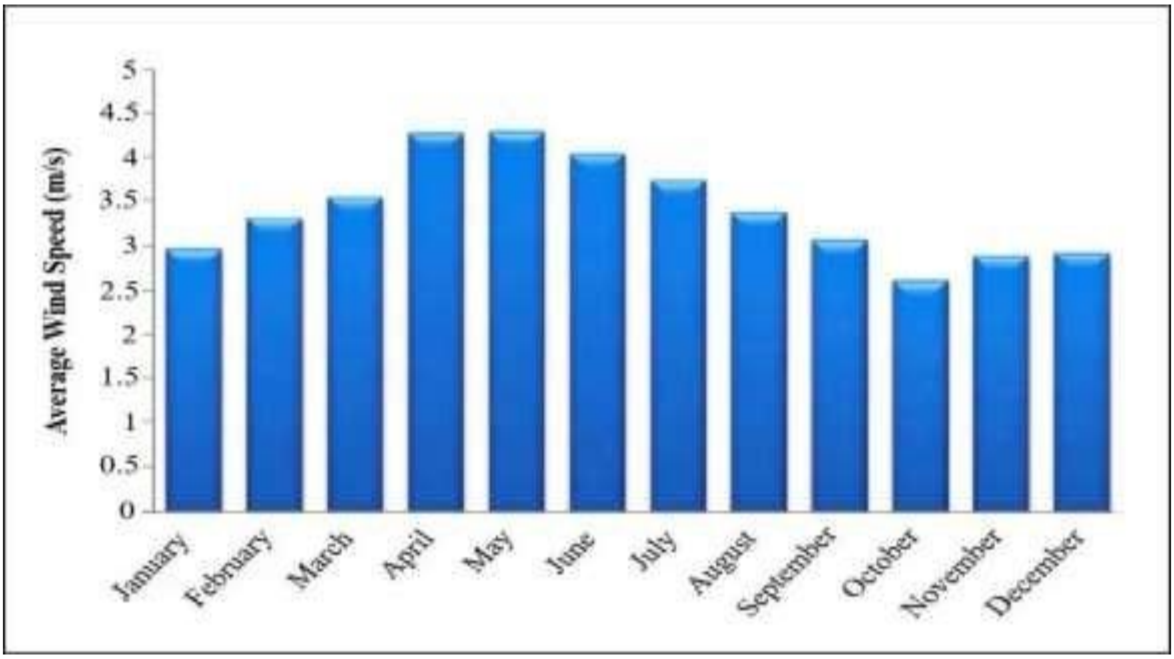

Fig. 3. Wind speed (monthly average)

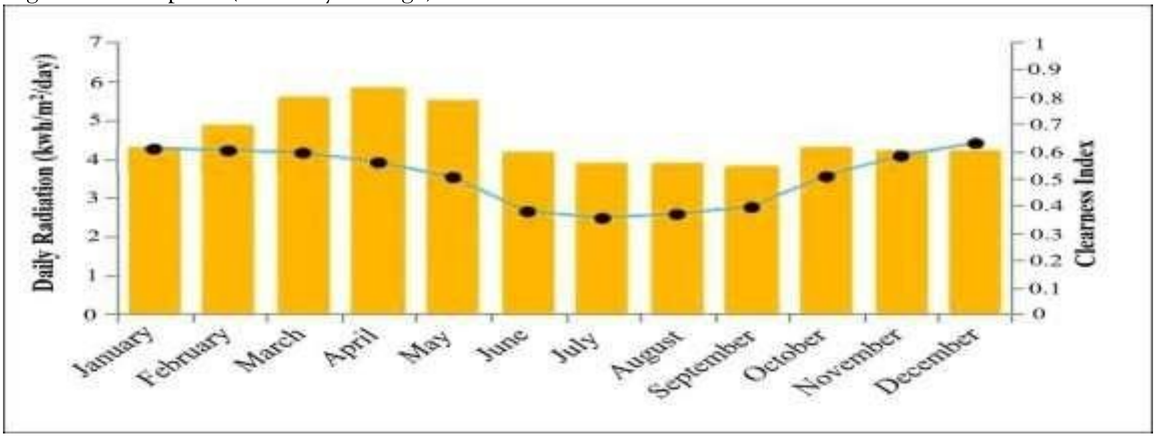

Fig. 4. Solar radiation and clearness index (monthly average)

III. METHODOLOGY

A. HOMER Software

HOMER software, developed by the National Renewable Energy Laboratory (NREL) in the United States, is widely used for designing and analyzing hybrid power systems [10]. In this study, HOMER is utilized by inputting data related to electrical load, solar radiation, wind speed, component specifications, and associated costs for system optimization.

B. Cost Analysis Methodology in HOMER [10, 11, 12]

1. Net Present Cost (NPC):

The NPC represents the total cost of system installation and operation over its lifetime.

$$(NPC) = \frac{(TAC)}{CRF(i,R_{prj})}$$

Where:

- TAC = Total annualized cost ($)
- CRF = Capital recovery factor
- i = Interest rate (%)
- Rprj = Project lifetime (years)

Total Annualized Cost (TAC):

The TAC includes the annualized costs of all system components, covering capital, operational, maintenance, replacement, and fuel expenses [12].

Capital Recovery Factor (CRF):

The CRF is a ratio used to determine the present value of a series of equal annual cash flows,

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where:

- n = Number of years
- i = Annual real interest rate

Annual Real Interest Rate:

The real interest rate accounts for the nominal interest rate and inflation and is given by [12]:

$$i' = \frac{i - F}{1 + F}$$

Where:

- i' = Real interest rate
- i = Nominal interest rate
- F = Annual inflation rate

Cost of Energy (COE):

The COE represents the average cost per kWh of useful electricity generated by the system and is calculated as [12]:

$$(COE) = \frac{(TAC)}{Lprim_{AC} + Lprim_{DC}}$$

Where:
- L_{prim},AC = AC primary load
- L_{prim},DC = DC primary load

IV. SIMULATION MODEL

The simulation process involves selecting and configuring various system components in HOMER to evaluate the performance and feasibility of different hybrid power system models. The primary objective is to compare the economic and technical viability of grid-connected and off-grid systems.

A. Grid-Connected Hybrid Power System

The grid-connected hybrid power system is designed to integrate solar photovoltaic (PV) panels, wind generators, a power converter, battery storage, and a grid connection. This configuration allows for a more stable and cost-effective energy supply by utilizing renewable sources while relying on the grid as a backup during periods of low renewable generation. Figure 5 illustrates the layout of this system in HOMER, highlighting the connections between components and their interactions.

In this model:
- The PV array and wind generator serve as the primary power sources, harnessing solar and wind energy to meet the load demand.
- A converter ensures smooth energy conversion between AC and DC systems.
- A battery bank stores excess energy to enhance reliability.
- The grid connection acts as a supplementary power source, supplying energy when renewable generation is insufficient and feeding excess power back to the grid when available.

This model reduces reliance on batteries, minimizing storage costs while ensuring an uninterrupted power supply.

B. Off-Grid Hybrid Power System

The off-grid system, as shown in Figure 6, follows a similar design but operates independently of the grid. It consists of PV panels, wind generators, batteries, a power converter, and the primary load but lacks a grid connection.

Key aspects of this system include:
- Increased reliance on battery storage, as there is no grid backup to compensate for fluctuations in renewable generation.
- Higher upfront costs, primarily due to the need for additional storage capacity to maintain energy reliability. • Enhanced energy independence, making it suitable for remote locations where grid access is limited or unavailable.

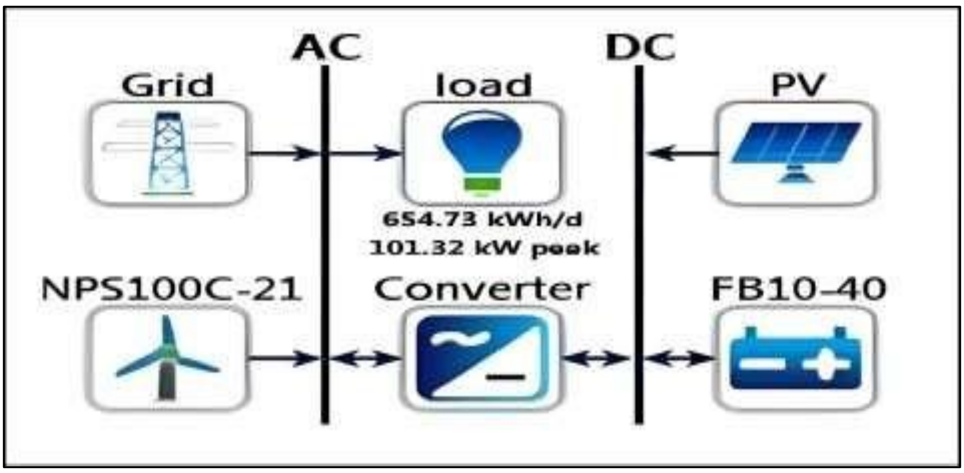

Fig. 5. The arrangement of hybrid power system (grid connected).

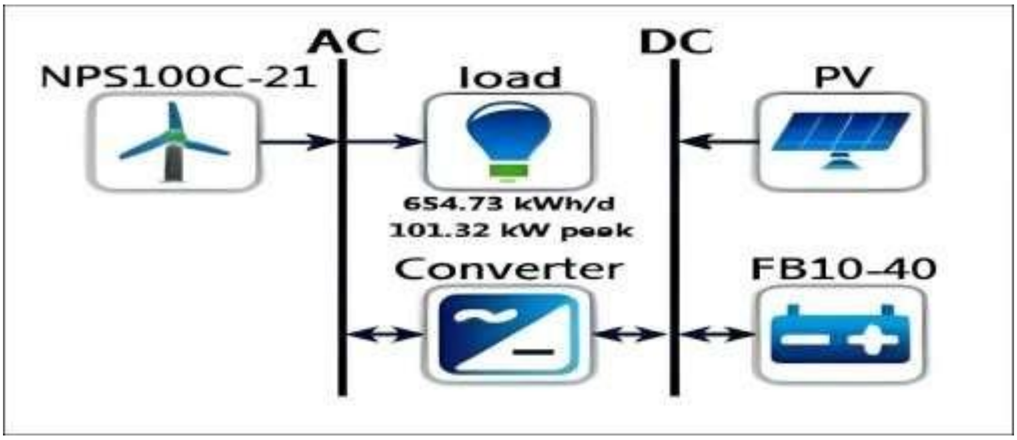

Fig. 6. The arrangement of hybrid power system (off-grid).

B. Wind Turbine (Converted to INR)

In this study, three Northern Power NPS100C-21 wind turbines, each with a capacity of 100 kW, are used [10]. The turbines have hub heights of 23m, 30m, and 37m, with a rotor diameter of 30.1m, and an estimated operational lifespan of 20 years.

- Capital Cost: ₹26,56,000 (₹26.56 lakh) per unit ($32,000 × 83)
- Operation & Maintenance Cost: ₹24,900 per unit ($300 × 83)

C. Power Converter

The system converter, manufactured by Generic, plays a crucial role in converting electrical energy between AC and DC as required by different components of the hybrid system. It operates with an efficiency of approximately 90% and has an expected lifespan of 20 years.

For economic evaluation:

- The capital cost of a 1 kW converter is estimated at ₹24,900 ($300 × 83).
- The replacement cost is also ₹24,900.
- The operation and maintenance cost is considered negligible, making it a cost-effective component in the system.

D. Battery Storage Bank

The battery storage bank selected for this study is the CELLCUBE® FB10-40, manufactured by Gildemeister. It has a storage capacity of 40 kWh and a lifetime energy throughput of 876,000 kWh. The battery operates with an efficiency of approximately 64%, ensuring backup power when needed.

• Role in the Hybrid System: o In the grid-connected system, the battery is primarily used during grid failures to ensure an uninterrupted power supply.

o In the off-grid system, it plays a more critical role by storing excess energy from solar and wind sources for use during periods of low generation.

E. Grid Connection

In a grid-connected hybrid system, the grid functions as both a backup power source and an excess power absorber.

- When renewable energy generation is insufficient, the grid supplies the shortfall to meet the demand.
- When excess energy is available, it can be fed back into the grid, improving overall efficiency and reducing dependence on energy storage solutions. Integration of Renewable Energy Sources

Given the renewable energy potential in the selected region (Anupgarh, Rajasthan), the hybrid power system is designed to utilize solar and wind energy as primary sources. A battery storage system is incorporated, particularly for off-grid operation, ensuring reliability and stability in power supply.

This system aims to provide a cost-effective, sustainable, and energy-efficient solution for meeting the electricity demands of the region while reducing dependency on fossil fuels.

V. OPTIMIZATION RESULTS AND PERFORMANCE ANALYSIS

The optimization results for the hybrid power system have been analyzed for both grid-connected and off-grid configurations. The results are depicted in Figures 7 and 8, showcasing a clear comparison of the economic feasibility and performance of each model.

A. Cost Optimization and Renewable Energy Contribution

- In the grid-connected system, as illustrated in Figure 7, the minimum cost of energy (COE) achieved is $0.0995 per kWh (approximately ₹8.25/kWh at an exchange rate of ₹83/USD).
- The renewable energy contribution in this configuration is 73%, meaning that a majority of the energy demand is fulfilled by solar and wind power.
- The hybrid system dynamically allocates an optimum number of renewable energy sources to supply electricity efficiently while minimizing reliance on the grid.

B. Off-Grid vs. Grid-Connected Economic Viability

- As seen in Figure 8, the off-grid hybrid system is significantly more expensive than the grid-connected model. • The COE for the off-grid system is $0.391 per kWh (approximately ₹32.45/kWh), which is nearly four times higher than that of the grid-connected system.
- The Net Present Cost (NPC), representing the total lifetime cost of the system, further highlights the economic difference: o Grid-connected system: $535,661 (₹4.44 crore) o Off-grid system: $1.21 million (₹10.04 crore)

This demonstrates that while an off-grid system provides energy independence, it comes at a substantially higher financial burden due to the increased need for battery storage and additional infrastructure. **C. Energy Production and Consumption Analysis**

- As depicted in Figure 9, the total yearly electricity generation by the proposed hybrid system is 436,186 kWh per year.
- The energy consumed by the load is 238,967 kWh per year, indicating a surplus of energy production.
- The excess energy is sold back to the grid, enhancing economic returns and improving system efficiency.

D. Monthly Energy Distribution and Seasonal Variations

- Figure 10 presents the monthly average electricity production from different power sources within the hybrid model.
- The data reveals seasonal variations, where solar energy production peaks during summer months, while wind energy production remains relatively steady throughout the year.
- This diversification of energy sources helps ensure reliable and consistent power generation, reducing the risk of shortages.

E. Key Findings and Practical Implications

- The grid-connected hybrid system proves to be the most cost-effective and efficient solution for the given location (Anupgarh, Rajasthan).
- Selling excess electricity to the grid provides additional economic benefits, improving the feasibility of the project.
- The off-grid system, while offering energy independence, is financially challenging due to high storage costs and infrastructure requirements.

Architecture					Cost				
PV (kW)	NPS100C-21	FB10-40	Grid (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
150	3		999,999	180	$0.0995	$535,661	-$4,977	$600,000	73
150	3	2	999,999	180	$0.101	$542,572	-$4,906	$606,000	73
200			999,999	180	$0.134	$662,548	$661.25	$654,000	62
200		2	999,999	180	$0.135	$669,536	$737.62	$660,000	62

Fig. 7. Screenshot of simulation for finding optimal design (grid connected).

Architecture				Cost				
PV (kW)	NPS100C-21	FB10-40	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
300	3	40	180	$0.391	$1.21M	$2,773	$1.17M	100

Fig. 8. Screenshot of simulation result of off grid power system (PV/Wind/Battery).

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Fig. 9. Snapshot of the production and consumption scenario.

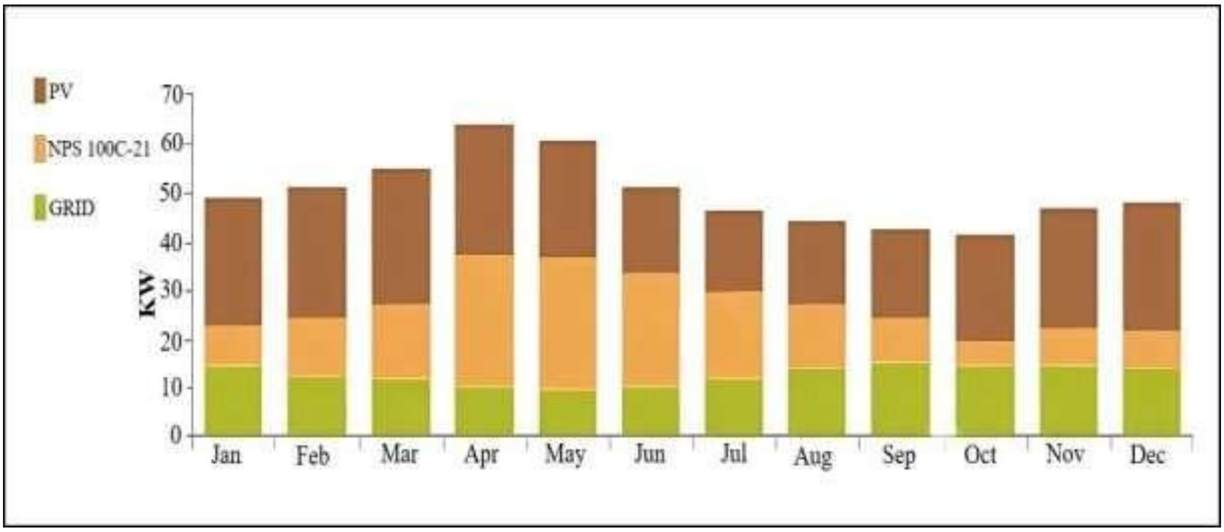

Fig. 10. Monthly average electricity production using the proposed model.

VI. CONCLUSION AND FUTURE RECOMMENDATIONS

This study provides a comparative analysis between off-grid and grid-connected hybrid power systems for a specific location (Anupgarh, Rajasthan, India). The optimization results clearly indicate that the gridconnected hybrid (PV/Wind) system is significantly more economical and efficient compared to the off-grid hybrid (PV/Wind/Battery) system for the same energy demand. Key Findings from the Study 1. Cost Efficiency: o The Net Present Cost (NPC) of the grid-connected hybrid system is substantially lower than that of the offgrid system. o The levelized cost of energy (COE) for the grid-connected model is nearly four times lower than the off-grid model, making it a more feasible solution for long-term sustainability.

2. Renewable Energy Utilization: o The off-grid system achieves 100% renewable energy integration but requires a large battery storage system to ensure power availability during non-generating hours (nighttime or low wind periods). o The grid-connected system, on the other hand, effectively balances renewable energy with grid support, eliminating the need for extensive battery storage. o The excess energy produced in the off-grid system goes unused, while in the grid-connected system, it is fed back into the grid, enhancing energy utilization and revenue generation.
3. Reliability and Practical Implementation:

o The grid-connected system ensures a continuous and stable power supply, making it a practical choice for rural electrification and industrial applications. o The off-grid system, despite offering energy independence, is financially challenging due to high battery and infrastructure costs.

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