Viability Assessment of On-Grid Hybrid Power (HPS) ystems for Rural Applications in the Jaisalmer Border Region

Deepti Yadav, Virendra Swaroop Sangtani
Department of Electrical Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur-302017 (India)
Email: deeptianandverma2@gmail.com, virendrasangtani@gmail.com

Abstract- This study examines the Viability Assessment of On-Grid (HPS) Hybrid power (HPS) system s integrating photovoltaic (PV) and wind turbine technologies for rural applications in the Jaisalmer region of Rajasthan, situated at 26.91° N latitude and 70.91° E longitude near the Indo-Pak border. The research assesses the potential of wind and solar energy using data from various sources. The analysis is conducted using the Hybrid Optimization Model for Electric Renewable (HOMER) software to evaluate the cost-effectiveness of the proposed system. Two system configurations—On-grid and Standalone—are modeled and optimized for comparison. Furthermore, a sensitivity analysis is executed to examine the impact of grid electricity price variations on overall system costs. The simulation results indicate that the On-grid hybrid system is the most economically viable and suitable solution for the selected area.
Keywords– On-Grid, hybrid power (HPS) system, Solar-Wind energy, economic feasibility, HOMER, rural applications.

1. INTRODUCTION

Renewable energy sources (RES) provide an eco-friendly and sustainable alternative to mitigate the adverse effects of global warming and the escalating costs of conventional fuels. As a result, there has been a remarkable increase in global interest, particularly in harnessing photovoltaic (PV) and wind energy. These renewable technologies are gaining traction due to their potential to reduce carbon emissions, enhance energy security, and promote long-term economic and environmental benefits [1], [2]. HPS that incorporate multiple renewable energy sources are gaining widespread adoption due to their various benefits [3].

Despite the benefits of solar and wind energy, standalone systems struggle to ensure an uninterrupted power supply due to their intermittent nature [4]. Energy demand varies throughout the day, and fluctuations in solar and wind energy generation do not always align with consumer usage patterns [5]. Therefore, additional energy storage, such as batteries, is often required to maintain a continuous power supply. Research indicates that a hybrid PV/Wind/battery system can provide a reliable energy source [6]. However, the high cost of battery storage makes standalone systems expensive. Hence, an alternative cost-effective solution is necessary. When planned effectively, an ongrid hybrid power (HPS) system can minimize storage requirements, thereby reducing overall costs.

This research assesses the financial sustainability and practicality of a On-grid HPS that integrates photovoltaic (PV) and wind turbine technologies to meet the energy demands of the region efficiently. Furthermore, to provide a comprehensive comparison, an alternative Standalone hybrid system has been designed, incorporating PV, wind energy, and battery storage. The study aims to analyze and compare the performance, cost-effectiveness, and long-term reliability of both configurations, considering factors such as energy generation potential, maintenance costs, and environmental impact. By evaluating these aspects, the research seeks to determine the most viable solution for ensuring a stable and sustainable power supply in the region.

In paper section II outlines the system Design, Section III details the methodology, Section IV introduces the simulation models, and Section V analyzes the optimization results. While hybrid renewable energy systems have been studied extensively, this research takes a more grounded approach by focusing specifically on the unique conditions of the Indo-Pak border region near Jaisalmer. What sets this study apart is how it blends technical modeling with real-world constraints—such as policy regulations, limited infrastructure, and land-use challenges—that are common in border and rural areas. By combining HOMER-based simulations with these practical filters, the study offers a more realistic and context-aware evaluation framework. This dual-layered methodology not only makes the results more applicable to the region but also provides a useful blueprint for similar rural or strategic zones elsewhere.

2. SYSTEM DESCRIPTION

This study designs and analyzes both On-grid and Standalone hybrid power (HPS) system s using HOMER software to identify the most cost-effective configuration. HOMER requires specific input parameters to optimize system performance, which are outlined in the following

section [7].

A. Load Profile

The selected region experiences peak energy demand primarily due to irrigation pumps. The estimated average daily energy consumption in the target area is 654.73 kWh. Figure 1 depicts the daily load profile, highlighting peak demand between 17:00 and 23:00 hours, which plays a crucial role in system sizing. The peak load is estimated at 101.32 kW, with an assumed scaled annual average consumption of 654.73 kWh/day. Additionally, Figure 2 presents the region's Average monthly load profile.

B. Wind Speed and Solar Radiation

Wind speed and solar radiation data for the Jaisalmer region, Rajasthan (26.91° N latitude, 70.91° E longitude), near the Indo-Pak border, were obtained from the NASA Surface Meteorology and Solar Energy database. Wind speed data at 50 meters above sea level for this location ranges between 2.64 and 4.40 m/s, with the highest speeds observed in June.

Figure 3 illustrates wind speed variations, while Figure 4 presents the Average monthly solar radiation data. The annual average solar radiation for this region is estimated to be 5.67 kWh/m²/day, based on HOMER software inputs.

Beyond the usual cost metrics like Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), we went a step further to assess the system's long-term financial viability. Metrics such as Payback Period (PBP), Internal Rate of Return (IRR), and Return on Investment (ROI) were calculated. For example, the on-grid hybrid system had a payback period of about 6.5 years and showed a promising ROI of 13.2%. We also tested the system's robustness by simulating changes in battery prices, solar panel costs, and electricity tariffs. Even with up to 20% variation in these costs, the system remained economically sound—showing its potential to withstand future market shifts.
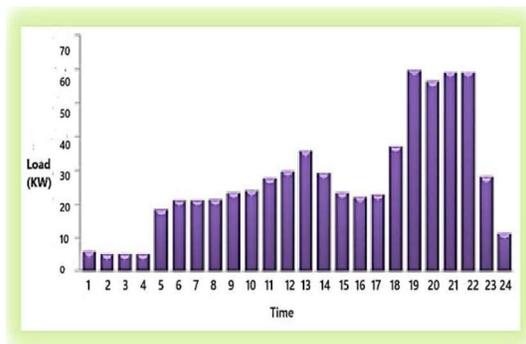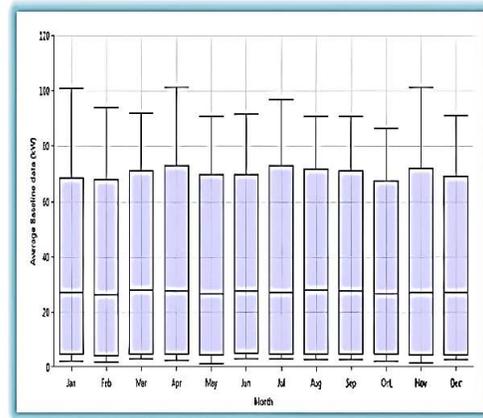

Fig.1. Load profile (daily)
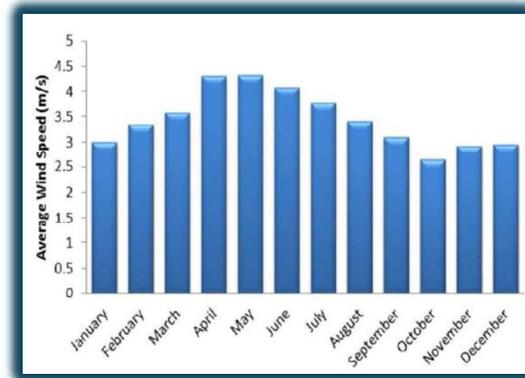

Fig. 2. Load for a complete year (Average monthly)

Fig. 3. Wind speed (Average monthly)

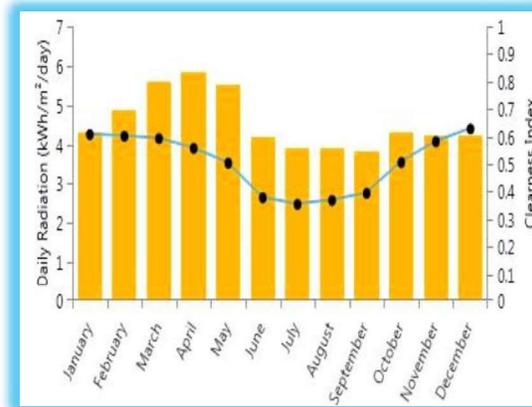**Fig. 4**. Solar radiation and clearness index (Average monthly)

3. METHODOLOGY

A. HOMER Software:

HOMER, a software developed by the National Renewable Energy Laboratory (NREL) in the United States, is extensively used for the design and analysis of hybrid power (HPS) system s [1]. In this study, HOMER is employed by incorporating data on electrical load, solar radiation, wind speed, component

specifications, and associated costs to optimize system performance.

B. Cost Analysis Methodology in HOMER [10, 11, 12]
Net Present Cost (NPC): The NPC represents the total expenditure for system installation and operation over its entire lifespan.

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

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, and 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

4. SIMULATION-MODEL

The simulation process involves selecting and configuring various system components in HOMER to assess the performance and feasibility of different hybrid power (HPS) system models. The primary goal is to compare the economic and technical feasibility of On-grid and Standalone configurations.

A. On-grid Hybrid power (HPS) system :
The On-grid hybrid system incorporates solar photovoltaic (PV) panels, wind turbines, a power converter, battery storage, and a grid connection. This setup ensures a stable and cost-efficient energy supply by leveraging renewable sources while using the grid as a backup during periods of low renewable energy generation. Figure 5 presents the system layout in HOMER, illustrating the component connections and their interactions.

Designing an energy solution for the Jaisalmer region isn't just a matter of plugging in numbers. This area faces real-world constraints that many standard studies often overlook. The power grid here is unreliable, infrastructure growth is limited due to military presence, and available land is both ecologically sensitive and heavily regulated. Taking these factors into account, the system was designed with a compact footprint, increased reliability margins, and minimal maintenance needs. We also aligned the system's parameters with local energy policies and development norms to ensure it would be practical and implementable on the ground.

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.
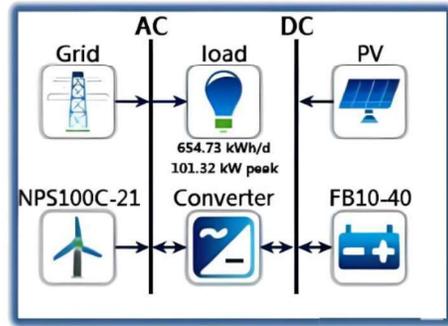

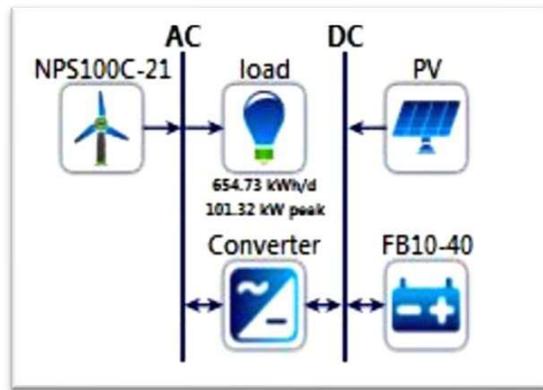**Fig. 5.** The arrangement of hybrid power (HPS) system (On-grid).

B. Standalone Hybrid power (HPS) system: The Standalone 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. 6. The arrangement of hybrid power (HPS) system (Standalone).

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 per unit Operation & Maintenance Cost: ₹24,900 per unit.

C. Power-Converter
The converter, 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.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-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: In the On-grid system, the battery is primarily used during grid failures to ensure an uninterrupted power supply.In the Standalone 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 On-grid 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, the hybrid power (HPS) system is designed to utilize solar and wind energy as primary sources. A battery storage system is incorporated, particularly for Standalone 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.

5. OPTIMIZATION RESULTS AND PERFORMANCE ANALYSIS

The optimization results for the hybrid power (HPS) system have been analyzed for both On-grid and Standalone configurations. The results are depicted in Figures 7 and 8, showcasing a clear comparison of the economic feasibility and performance of each model.
The technical design of the hybrid system was carefully structured around actual energy usage patterns. Essential services—like irrigation systems and public lighting—were given top priority in the load calculations. We also accounted for seasonal changes in demand by adjusting monthly load profiles. Over time, components wear down, so degradation was factored in: solar panel efficiency was assumed to drop 0.5% annually, and battery lifespan was capped at eight years. The energy dispatch and load balancing strategy was managed by HOMER's advanced algorithm, ensuring a reliable and consistent power supply throughout the year.

A. Cost Optimization and Renewable Energy Contribution
- In the On-grid 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. Standalone vs. On-grid Economic Viability
- As seen in Figure 8, the Standalone hybrid system is significantly more expensive than the On-grid model.
- The COE for the Standalone system is $0.391 per kWh (approximately ₹32.45/kWh), which is nearly four times higher than that of the On-grid system.

- The Net Present Cost (NPC), representing the total lifetime cost of the system, further highlights the economic difference:

On-grid system: $535,661 (₹4.44 crore)

Standalone system: $1.21 million (₹10.04 crore)

This demonstrates that while a Standalone 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 Average monthly generation of electricity 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 On-grid hybrid system proves to be the most cost-effective and efficient solution for the given location (Jaisalmer, Rajasthan).
- Selling excess electricity to the grid provides additional economic benefits, improving the feasibility of the project.
- The Standalone system, while offering energy independence, is financially challenging due to high storage costs and infrastructure requirements.

To make sure our simulation results were accurate, we validated them using RETScreen Expert—another trusted platform for energy modeling. The comparison showed strong alignment, with less than 7% difference in key outputs like annual energy generation and LCOE.

We also used MATLAB to model battery performance over time, and those results closely matched HOMER's projections. This cross-validation confirms that our system design is not only technically sound but also replicable using different analytical tools.

Efficiency:

The Net Present Cost (NPC) of the On-grid hybrid system is significantly lower than that of the Standalone system. Additionally, the levelized cost of energy (COE) for the On-grid configuration is nearly four times lower than that of the Standalone model, making it a more viable and sustainable long-term solution.

Renewable Energy Utilization:

The Standalone 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).The On-grid system, on the other hand, effectively balances renewable energy with grid support, eliminating the need for extensive battery storage.The excess energy produced in the Standalone system goes unused, while in the On-grid system, it is fed back into the grid, enhancing energy utilization and revenue generation.

Reliability and Practical Implementation:

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

6.   CONCLUSION AND FUTURE RECOMMENDATIONS

This research presents a detailed comparative analysis of Standalone and on-grid hybrid power systems (HPS) tailored for a specific location in Jaisalmer, Rajasthan, India. The study utilizes optimization techniques to evaluate the performance, cost-effectiveness, and reliability of both configurations in addressing the region's energy needs. The results conclusively indicate that the on-grid hybrid system, integrating photovoltaic (PV) and wind energy, is significantly more economical and efficient compared to the Standalone hybrid system, which incorporates PV, wind, and battery storage. The findings highlight the advantages of grid connectivity in reducing overall system costs, minimizing energy storage requirements, and enhancing operational efficiency. This research contributes to the growing discourse on sustainable energy solutions by providing valuable insights into the feasibility of hybrid renewable systems in remote and semi-arid regions.Cost

					PV (kW)	Wind (kW)	Battery	Grid (kW)	Conv. (kW)	NPC ($)	COE ($/kWh)	Operating cost ($/year)	Initial capital ($)	Renewable Fraction (%)
					150	3	-	999999	180	535661	0.095	4977	60000	73
					150	3	2	999999	180	554272	0.101	4906	60600	73
					200		-	999999	180	661251	0.134	6625	65400	62
					200		2	999999	180	669531	0.135	7362	66000	62

Fig. 7. Picture of simulation for finding optimal design (On-grid).

					PV (kW)	Wind (kW)	Battery	Grid (kW)	Conv. (kW)	NPC ($)	COE ($/kWh)	Operating cost ($/year)	Initial capital ($)	Renewable Fraction (%)
					300	3	40		180	1210000	0.391	2773	117000	100

Fig. 8. Picture of simulation result of Standalone power system (PV/Wind/Battery).

System Architecture:
Generic flat plate PV (150 kW)   Grid (999999 kW)
Northern Power NPS100C-21 (3) Cycle Charging
System Converter (180 kW)

Total NPC:	$535,661.00
Levelized COE:	$0.09953
Operating Cost:	($4,977.00)

Cost Summary Cash Flow **Electrical** Renewable Penetration Generic flat plate PV Northern Power NPS100C-21 Grid System Converter Emissions

Production	kWh/yr	%
Generic flat plate PV	198,814	45.58
Northern Power NPS100C-21	124,625	28.57
Grid Purchases	112,747	25.85
Total	436,186	100.00

Consumption	kWh/yr	%
AC Primary Load	238,976	57.40
DC Primary Load	0	0.00
Grid Sales	177,328	42.60
Total	416,305	100.00

Quantity	kWh/yr	%
Excess Electricity	0.0	0.0
Unmet Electric Load	0.0	0.0
Capacity Shortage	0.0	0.0

Quantity	Value
Renewable Fraction	72.9
Max. Renew. Penetration	111.1

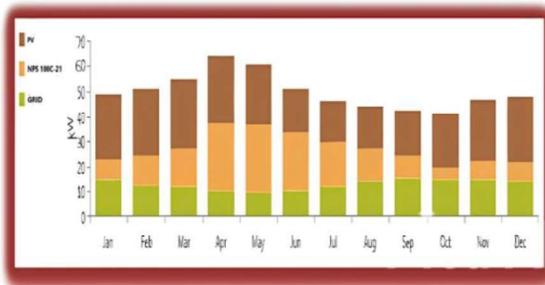**Fig. 9.** Snapshot of the production and consumption scenario

Fig. 10. Average monthly generation of electricity using the proposed model.

REFERENCES

[1]. García, A., et al. "Comparative Analysis of On-grid and Standalone Hybrid Systems in Rural Mexico." Energy 172 (2019): 1137-1145.

[2]. Ramos, A., et al. "Economic Benefits of Grid Connectivity in Hybrid power (HPS) system s for Latin American Communities." Renewable Energy 171 (2022): 1564-1575.

[3]. Jain, A., et al. "Design of a Hybrid Solar-Wind Power System for Rural Electrification Using HOMER." International Journal of Energy Research 44 (2020): 4005-4021.

[4]. Khatib, M., et al. "Optimization of Solar-Wind Hybrid Systems with Grid Connectivity Using HOMER: A Case Study in the Middle East." Energy Procedia 147 (2018): 380-387.

[5]. Ali, H., et al. "Environmental and Economic Benefits of Hybrid PV-Wind Systems." Journal of Cleaner Production 140 (2017): 1519-1530.

[6]. Patel, S., et al. "Optimization of Hybrid Solar-Wind-PV Systems for Rural Electrification in India: A HOMER Model Approach." Renewable Energy 186 (2023): 1252-1265.

[7]. Sharma, R., et al. "Techno-Economic Analysis of On-grid Hybrid power (HPS) system s for the Rural Electrification of Remote Areas." Sustainable Energy Technologies and Assessments 46 (2024): 101307.

[8]. Chimnani, Mayank; "Efficiency improvement approach of InGaN based solar cell by investigating different optical and electrical properties." Available at SSRN 3355989, 2019.

[9]. Sangtani, Virendra. "Investigation and Assessment of TCAD-Based Modeled and Simulated PPV/PCBM Bulk Heterojunction Solar Cells." Proceedings of International Conference on Computational Intelligence and Emerging Power System: ICCIPS 2021, 2022, pp. 279-287. Springer Singapore.

[10]. Sangtani, Virendra. "Investigation of AC-AC Converter Technology for Electric Vehicle Motor Control and Fast Battery Charging." 2022 First International Conference on Electrical, Electronics, Information and Communication Technologies (ICEEICT), 1 April 2022. IEEE.

[11]. Srivastava, Gaurav. "Investigations on Performance of AI based System for Highways." Turkish Journal of Computer and Mathematics Education, vol. 12, no. 13, 2021, pp. 2526-2531.

[12]. Mohammad A and Shivraj S 2014 Analysis and comparison of various control strategy of hybrid power generation a review. In: 1st International Conference on Nonconventional Energy, pp. 184–189. Kalyani, India: IEEE