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Optimization and Economic Analysis of a Grid-Connected Hybrid Power System for the Jaisalmer Region, Rajasthan

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Abstract:

This study examines the design and optimization of a grid-connected hybrid power system for the Jaisalmer region in Rajasthan, situated at 26.91° N latitude and 70.91° E longitude, near the Indo-Pak border. The primary goal is to fulfill the region's energy requirements by integrating renewable energy sources, specifically solar photovoltaic (PV) and wind turbines, with grid supply and battery storage. Energy demand was estimated based on local consumption patterns, with a daily average load of 654 kWh and a peak demand of 110 kW, particularly during irrigation hours. Seasonal fluctuations were considered, with significant demand surges observed during the monsoon months (June to September). The region's solar energy potential was evaluated, showing an average solar irradiance of 5.6 kWh/m²/day, while wind speeds varied between 3.0 m/s and 4.0 m/s.The system was modeled using HOMER Pro software, analyzing four different configurations: (1) Solar PV, wind turbines, grid supply, and lithium iron phosphate (LFP) battery; (2) Solar PV, wind turbines, grid supply without battery; (3) Solar PV, wind turbines, grid supply with lead-acid battery; and (4) Solar PV, wind turbines, and grid supply without storage. The estimated annual energy demand ranged from 216,755 kWh to 296,121 kWh, depending on the configuration. The Net Present Cost (NPC) was computed for each setup, revealing that Combination 1 (Solar PV, Wind Turbines, Grid Supply, and Battery) incurred an NPC of $320,201, whereas Combination 4 (Solar PV, Wind Turbines, and Grid Supply without Storage) had the lowest NPC at $227,092. Configurations incorporating battery storage, such as Combination 1, provided a stable energy supply with up to 6.07% surplus, whereas systems without storage exhibited greater energy availability fluctuations.The economic analysis indicated that although battery storage increased upfront costs, it significantly improved energy security and system reliability. The findings suggest that a grid-connected hybrid power system with battery storage presents the most viable solution

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for the Jaisalmer region, offering an optimal balance between cost-effectiveness, energy reliability, and sustainability. The study's optimization results provide valuable guidance for rural electrification initiatives, promoting reduced grid dependency and lower environmental impact. Future research could explore advancements in battery technologies and grid management strategies to enhance system efficiency and further reduce costs.

Keywords: Grid-connected, hybrid power system, renewable energy, economic feasibility, HOMER, rural applications.

I. INTRODUCTION:

Access to reliable, sustainable, and affordable electricity remains a critical challenge in remote regions, particularly in areas with limited grid connectivity. This issue is especially pronounced in the Jaisalmer region of Rajasthan, near the Indo-Pak border, where power infrastructure is scarce and unreliable. Hybrid power systems, integrating renewable sources like solar photovoltaic (PV) and wind energy with grid connectivity, offer a viable solution. Such systems leverage local renewable resources while utilizing grid backup to ensure continuous power supply, reducing dependence on costly battery storage.This study evaluates the economic feasibility of a grid-connected hybrid power system in this region using the Hybrid Optimization Model for Electric Renewables (HOMER) software. By simulating various configurations, the research aims to determine the most cost-effective and technically viable solutions. Prior studies highlight the benefits of hybrid systems in rural electrification. Sikandar et al. (2020) [1] found hybrid PV-wind systems effective for remote villages in Pakistan, while Kumar et al. (2021) [2] demonstrated their cost efficiency in India. Additionally, García et al. (2019) [3] and Ramos et al. (2022) [4] showed that grid-connected hybrid systems significantly reduce Net Present Cost (NPC) by lowering storage requirements and operational costs.HOMER has been widely used to optimize hybrid power configurations. Jain et al. (2020) [5] and Khatib et al. (2018) [6] confirmed the cost-effectiveness of grid-connected hybrid models, with Sharma et al. (2024) [7] reinforcing their efficiency in Rajasthan. Beyond economic benefits, hybrid systems contribute to environmental sustainability, reducing CO_2 emissions by up to 40% (Ali et al., 2017). Patel et al. (2023) [8] and Sharma et al. (2024) [9] further emphasize their role in promoting energy security and rural development. This research provides insights into hybrid power adoption for remote areas, ensuring economic viability and sustainability.

III. PROBLEM STATEMENT:

Rural and isolated regions, particularly those located near the Indo-Pak border in Rajasthan (such as the Jaisalmer district), face significant challenges in terms of reliable and continuous access to electricity. The existing infrastructure in these remote areas is often inadequate to meet the growing demand for energy. Traditional grid extension is costly and impractical due

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to the geographical isolation and the socio-political context of the region.In such areas, renewable energy sources like solar and wind offer a promising solution, but their intermittent nature makes them less reliable when used as standalone systems. Integrating renewable energy sources into a hybrid system, along with grid connectivity, could provide a reliable and cost-effective power supply. However, the economic feasibility of such systems in a region like Jaisalmer—where energy demand is variable and renewable energy potential is both abundant and underutilized—has not been sufficiently explored.

This study addresses the gap by analyzing the economic viability of a **grid-connected hybrid power system** that integrates **solar photovoltaic (PV)** and **wind turbine** systems in the Jaisalmer region. The goal is to assess the economic and technical performance of the system, compare it with traditional grid power, and determine the most cost-efficient approach to electrification in this border region. This analysis is crucial for providing a sustainable and affordable energy solution that can be scaled up for other similar regions facing similar challenges.

IV. METHODOLOGY

The methodology of this study employs a structured, data-driven approach to evaluate the feasibility and economic viability of a **grid-connected hybrid power system** using **solar** and **wind energy** for the **Jaisalmer region, Rajasthan, located at 26.91° N latitude and 70.91° E longitude, near the Indo-Pak border** of Rajasthan. The goal is to determine whether a hybrid system can meet the energy demand of this region, considering its geographical, climatic, and economic factors. The study will incorporate **system design**, **load analysis**, **renewable energy potential**, and **economic evaluation**. The following steps outline the methodology:

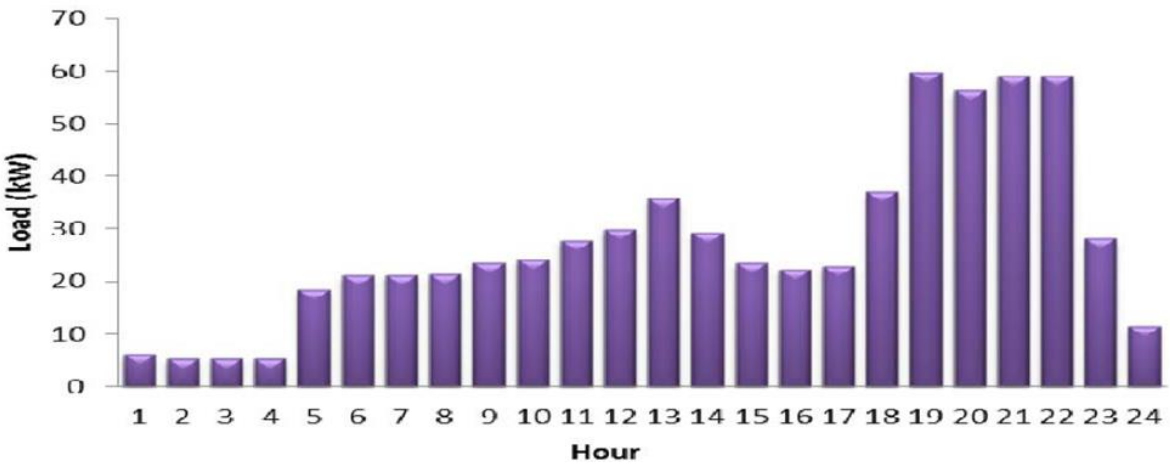

Fig.1. Load profile (daily).

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1. Area Selection

The **Jaisalmer region, Rajasthan, located at 26.91° N latitude and 70.91° E longitude, near the Indo-Pak border**, has been selected for this study due to its significant renewable energy potential and the region's lack of consistent access to electricity [10]. The region is characterized by:

- **High Solar Irradiance**: Average daily solar radiation levels of approximately **5.6 kWh/m²/day**, which is ideal for solar PV generation.
- **Moderate Wind Speed**: The wind speeds in the region range from **2.5 m/s to 5.0 m/s**, making it suitable for small to medium-scale wind turbine installations.

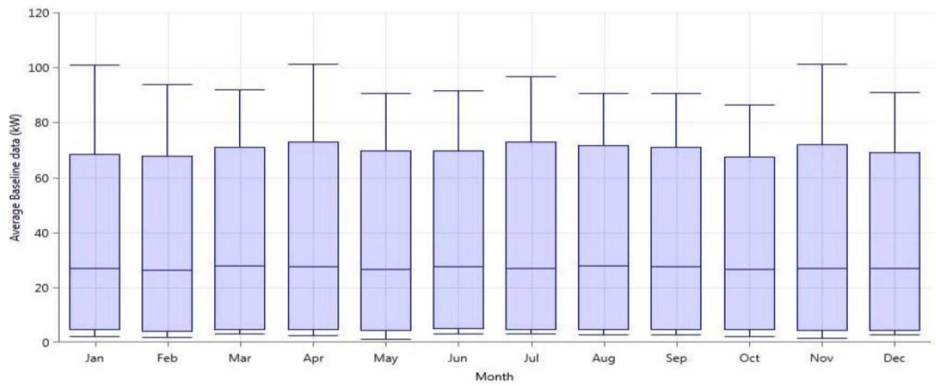

Fig. 2. Load for a complete year (monthly average).

2. Energy Demand Estimation

The first step in designing the hybrid power system is estimating the **energy demand** of the Jaisalmer region. Energy demand in rural areas like Jaisalmer typically varies depending on **daily household consumption** and **agricultural activities**. The key assumptions for energy demand estimation are:

- **Daily Average Load**: The typical energy consumption in rural Rajasthan can be estimated at **654 kWh/day** for an average village with **500 households** and some community-based agricultural operations.
- **Peak Load Demand**: Based on irrigation schedules, peak demand can reach up to **110 kW** during certain hours when irrigation pumps are activated, typically between **17:00 and 23:00 hrs**.

3. Source Estimation

A hybrid system will be designed to combine **solar photovoltaic (PV)** and **wind turbines** to meet the energy demand in a cost-effective and sustainable manner. The energy generation

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potential from these sources is estimated based on the region's resource data shown in figure 3.

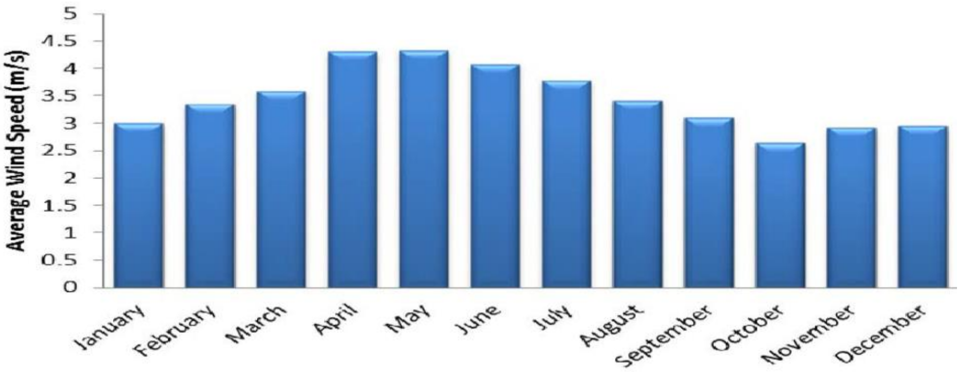

Fig. 3. Wind speed (monthly average).

- **Solar Energy Potential**:

Solar Irradiance: The region receives an average of **5.6 kWh/m²/day**, which is above average for Rajasthan, a state known for its high solar potential.

Solar System Sizing: Based on the estimated daily load of **700 kWh**, a **solar PV system** with an efficiency factor of 15% and panel conversion efficiency of 18% would require approximately **150-160 kW** of installed capacity to meet daily needs.

- **Wind Energy Potential**: **Average Wind Speed**: The average annual wind speed is between **3.0 m/s and 4.0 m/s**. With a **hub height of 50 meters**, the typical **power curve** for small to medium-scale wind turbines indicates that **3 to 5 turbines**, each with a **capacity of 10-20 kW**, could meet a substantial portion of the energy demand, especially during periods of low solar radiation. Solar radiation and clearness index (monthly average) shown in Fig. 4.

- **Wind System Sizing**: Wind energy production varies seasonally, with higher production during the **winter and spring months (October to April)** when wind speeds tend to be higher.

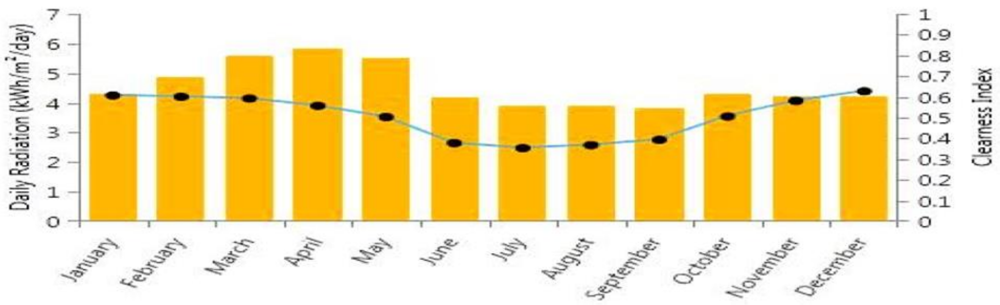

Fig. 4. Solar radiation and clearness index (monthly average).

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These renewable energy sources are integrated with the grid to ensure continuous supply, as the **grid serves as a backup** during periods when renewable generation is insufficient.

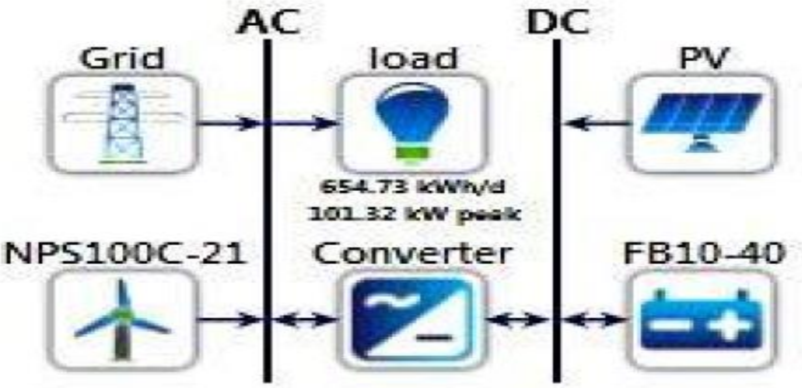

Fig. 5. The arrangement of hybrid power system (grid connected).

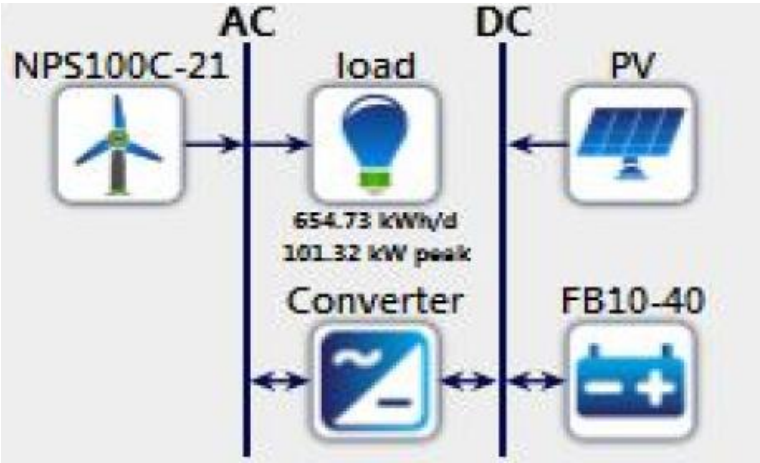

Fig. 6. The arrangement of hybrid power system (Renewable only).

4. Economic Feasibility Analysis

The economic evaluation of the grid-connected hybrid power system will be conducted by analyzing the following parameters:

- **Net Present Cost (NPC)**: The total cost of the system, including **installation, operation**, and **maintenance costs**, discounted over the system's lifetime.
- **Cost of Energy (COE)**: The average cost per unit of energy produced by the hybrid system, which is a key metric for evaluating the system's economic viability.
- **Break-Even Point**: An analysis of the time required for the hybrid system to recover its initial investment and start generating savings compared to conventional grid power.

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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 [1]. 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]

Net Present Cost (NPC): The NPC represents the total cost of system installation and operation over its lifetime.

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

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

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- 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

System Architecture:	Generic flat plate PV (150 kW)	Grid (999999 kW)	Total NPC:	$535,661.00
	Northern Power NPS100C-21 (3)	Cycle Charging	Levelized COE:	$0.09953
	System Converter (180 kW)		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. 7. Snapshot of the production and consumption scenario.

V. OPTIMIZATION THROUGH HOMER PRO SOFTWARE

HOMER Pro, developed by the **National Renewable Energy Laboratory (NREL)**, is an advanced tool used for modeling and optimizing hybrid renewable energy systems, including grid-connected solutions [11]. This study utilizes **HOMER Pro** to design an optimized hybrid system for the **Jaisalmer region** in Rajasthan. The software allows for detailed simulation and analysis of system configurations, ensuring that the designed system meets energy demand efficiently while considering both **technical** and **economic constraints**.

5.1. Simulation Analysis

The core of the system design process in HOMER Pro revolves around the selection and sizing of the energy system components [12]. The software simulates the performance of various configurations based on the chosen components, including **solar PV systems**, **wind turbines**, and grid integration. The main objectives of the simulation are to determine:

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- **System Configuration**: The software explores various component combinations to meet the energy demand of the region. In this study, the hybrid system includes **solar PV**, **wind turbines**, and grid connectivity, while excluding biomass, biogas, and fuel cells as energy sources.

- **Energy Production and Cost Optimization**: HOMER Pro calculates the energy production from each renewable source and determines the **total system cost**, including **capital**, **operational**, and **maintenance costs**. It also estimates the **replacement** and **fuel costs** for the system.

5.2. Sensitivity Analysis

Sensitivity analysis is an essential part of the optimization process, allowing for the evaluation of how changes in certain parameters affect the overall performance of the hybrid system. These parameters, or sensitivity factors, are **variables that the designer cannot control** but must account for in the model [13].

In this study, the following **sensitivity factors** are considered:

- **Solar radiation levels** at the site, which impact the solar energy generation.

- **Wind turbine costs**, as fluctuations in wind turbine pricing affect the overall economic feasibility.

- **Battery costs**, which significantly influence the capital and maintenance costs of the hybrid system.

- **Fuel costs** for grid energy or any backup generation.

In the proposed system, the **availability of renewable energy sources** in the region is modeled to determine the capacity of **solar PV systems** and **wind turbines** that would most effectively meet the region's demand [13].

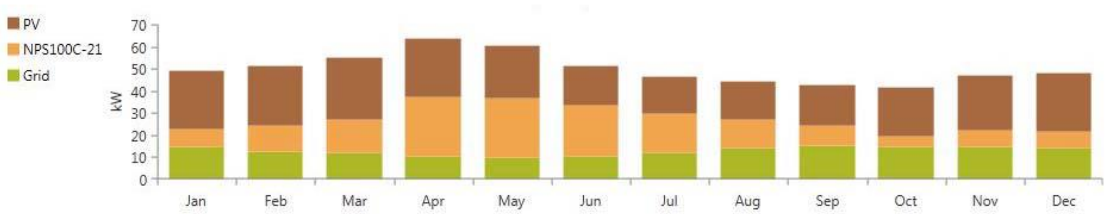

Fig. 8. Average electricity production using the proposed model.

After performing the hourly simulation and sensitivity analysis, several configurations with varying component sizes and costs are generated. The results highlight the most efficient system configuration, offering a balance between economic feasibility and energy reliability. Key findings include the ideal combination of wind and solar energy, the optimal battery size,

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and the overall reduction in grid dependency, resulting in both cost savings and sustainability [15].

VI. RESULTS AND COMPARISONS OF DIFFERENT SITUATIONS

The study evaluates hybrid renewable energy systems integrating Solar PV (SPV), Wind Turbine Generators (WTG), Grid Supply, and Battery Storage to meet energy demands in a rural area near Jaisalmer, Rajasthan. Using HOMER Pro software, four different system configurations were optimized and analyzed for efficiency, cost, and energy production.The four configurations show distinct variations in energy production and system costs:

- **Combination-1 (SPV-WTG-Grid Supply-LFP Battery):** The system comprises 100 kW SPV, 57 kW Grid Supply, and 50 Wind Turbines. It meets an annual energy demand of **238,266 kWh**, with **6.07% surplus energy availability**.
- **Combination-2 (SPV-WTG-Grid Supply without Battery):** Excluding battery storage, this configuration has the same SPV, Grid, and Wind capacities as Combination-1 but meets an increased energy demand of **296,121 kWh/year**, with **4.86% surplus energy**.
- **Combination-3 (SPV-WTG-Grid Supply-Lead Acid Battery):** This system, with 100 kW SPV, 60 kW Grid, 50 Wind Turbines, and 200 Batteries, results in an energy demand of **227,092 kWh/year** and a **20.65% surplus**.
- **Combination-4 (SPV-WTG-Grid Supply without Storage):** Without batteries or fuel cells, it uses 100 kW SPV, 60 kW Grid, and 50 Wind Turbines, meeting an energy demand of **216,755 kWh/year** with **33.53% surplus energy**.

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. 9. 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. 10. Screenshot of simulation result of off grid power system (PV/Wind/Battery).

VII. Conclusion

This study analyzes hybrid renewable energy systems in a rural area near Jaisalmer, Rajasthan, focusing on Solar PV, Wind Turbines, and Grid Supply. The findings highlight that a grid-connected hybrid system with battery storage effectively balances reliability and cost.

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Combination-1 and Combination-3 ensure stable energy generation with surplus power, while Combination-2 and Combination-4, which exclude battery storage, lower costs but risk energy shortages during low renewable generation periods. Battery storage enhances system stability, particularly in SPV-WTG-Grid configurations, ensuring a continuous power supply throughout the year. From an economic standpoint, grid supply and solar PV are the most cost-effective components, while battery storage, though increasing initial costs, and significantly improves reliability. The total net present cost (TNPC) analysis indicates that storage-inclusive combinations, such as Combination-1, provide an optimal balance between cost efficiency and energy security. Overall, the grid-connected hybrid system emerges as the most viable option, offering economic feasibility and minimal environmental impact. Future research could focus on integrating advanced grid management strategies and hybrid battery technologies to optimize costs and system performance further.

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