Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 10, October - 2025

Dynamic Analysis of Solar Power Generation and Critical Challenges in Developing Solar–Wind Hybrid Standalone Energy Systems

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***ABSTRACT*: Solar wind hybrid systems are gaining attention due to their complementary energy source. These hybrid systems can be grid-connected or standalone. Designing such systems for off-grid applications requires energy storage options like batteries. The paper presents the dynamic analysis of solar power generation for a tiny 2 kW system that can be made portable. This study explores the fundamentals of solar-wind hybrid systems, addressing key issues and critical challenges in development, along with problems related to energy storage options. Features like higher reliability and reduced intermittency, energy independence and security, economic and environmental benefits, and system flexibility are discussed in detail. The study also covers challenges such as technical and design issues, economic and financial barriers, and storage-specific problems.**

***KEYWORDS:* Solar Power Generation, Wind Power Generation, Solar-Wind Hybrid Generation, Critical Challenges**

INTRODUCTION:

Solar-wind hybrid standalone systems have become increasingly popular for remote area applications, especially at lower ratings of 1-10 kW. These systems can provide a reliable power supply where wind and solar resources are moderate to high, making them beneficial in locations where grid connection is a significant challenge [1-3]. Figure 1 illustrates the basic components of the solar-wind hybrid system, which includes batteries for energy storage and a DC lamp or similar load.

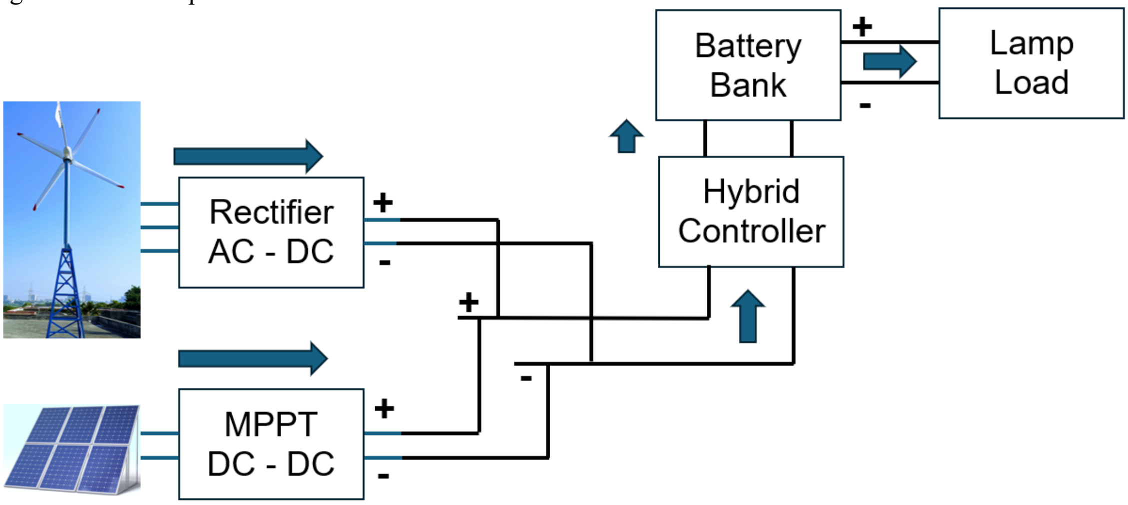

Figure1. Solar Wind Hybrid Off-grid System with Battery Bank and a Load

As a known fact, solar photovoltaic generation and wind power generation depend on the location. In Figure 1, solar photovoltaic generation energy is DC, and the standard energy bus is also DC. Still, to extract the maximum power from these panels and supply it to the load at the DC bus voltage, a maximum power point tracking (MPPT) mechanism is required [4-8]. Wind power generation, being a rotational device, is AC, and therefore a rectifier converts AC to DC and adjusts it to the DC bus voltage. The hybrid controller manages the charging of the batteries

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at the appropriate voltage. It ensures optimal charging of the battery bank and safe power delivery to the load. A battery bank may consist of several batteries as an energy storage option, depending on the load requirements [9-11].

METHODOLOGY:

The most versatile and valuable software for the simulation and design of solar power generation estimation is PVsyst. PVsyst provides reliable data from Meteonorm 8.2, and for the Rajkot, Gujarat, India location, this data is presented in Table 1.

Table 1. Solar Power Generation and Wind Velocity at Rajkot, Gujarat, India

Site: Rājkot (India)
Data source: Rājkot_MN82.SIT -- Meteonorm 8.2 (1996-2015), Sat=100%

	Global horizontal irradiation	Horizontal diffuse irradiation	Temperature	Wind Velocity
	kWh/m²/mth	kWh/m²/mth	°C	m/s
January	145.8	36.7	20.2	2.40
February	150.7	44.0	23.2	2.60
March	191.5	64.0	28.0	3.09
April	203.7	76.1	31.2	4.10
May	213.4	88.2	33.1	5.20
June	160.2	96.5	31.4	5.00
July	115.7	83.0	28.9	4.59
August	117.5	89.0	27.8	4.20
September	140.4	77.2	27.9	3.39
October	158.3	67.5	29.7	2.30
November	136.0	51.1	25.9	1.89
December	129.3	43.8	21.8	2.20
Year	**1862.5**	**817.1**	**27.4**	**3.4**

Solar power generation capacity per month per kilowatt (kW) of installed capacity, along with the average wind velocity, can be plotted as shown in Figure 2. It is clear from the bar graph that April, May, and June could be highly productive months for energy generation using these hybrid sources. Solar power generation may peak in April and May, while wind power primarily peaks in May and June. During these months, more energy can be stored and released by the batteries. Simulations for solar power generation, depicted in Figure 3, show a performance ratio of 0.814, or 81.4%, for the system at the Rajkot location. The simulation used a small 2 kW solar power plant with six 335 W solar panels (335 W * 6 = 2010 W = 2.01 kW). The total energy produced per kW of installed capacity was 1,653 kWh annually, with a normalized production of 4.53 kWh/kWp/day.

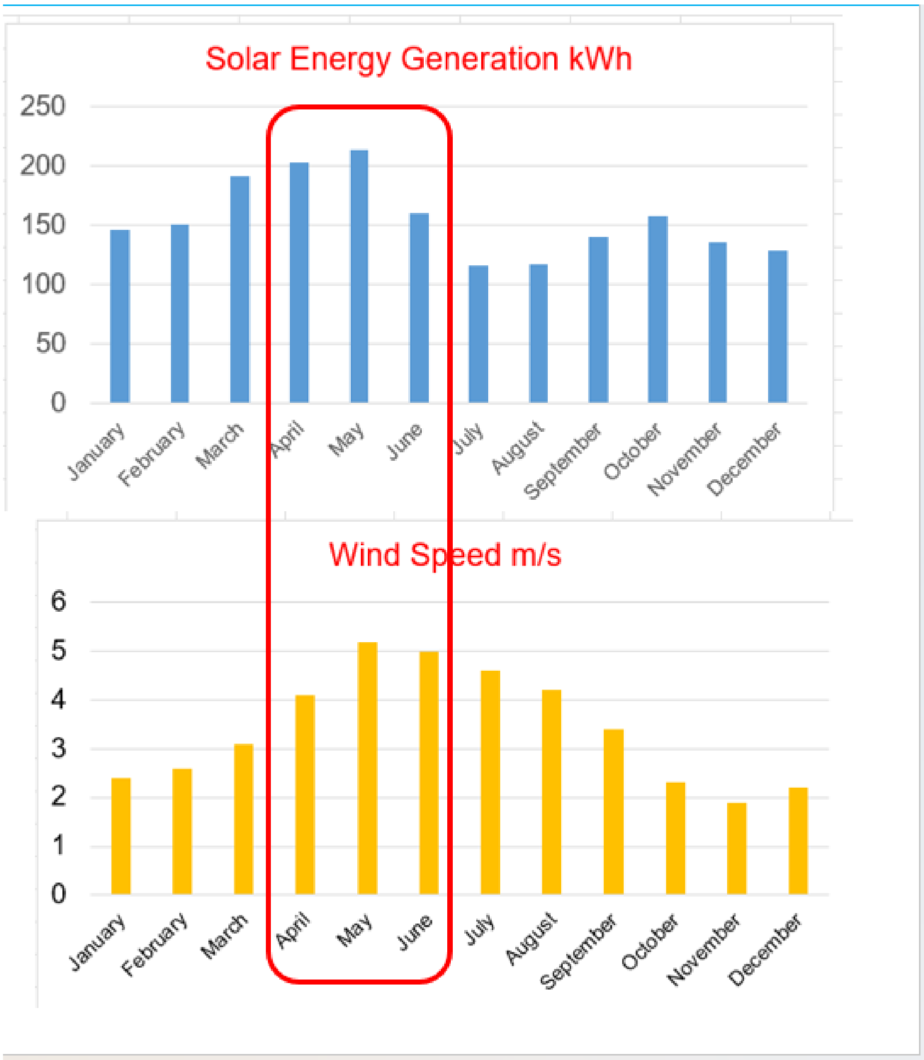

Figure 2. Solar Power Generation and Wind Velocity Estimation Data

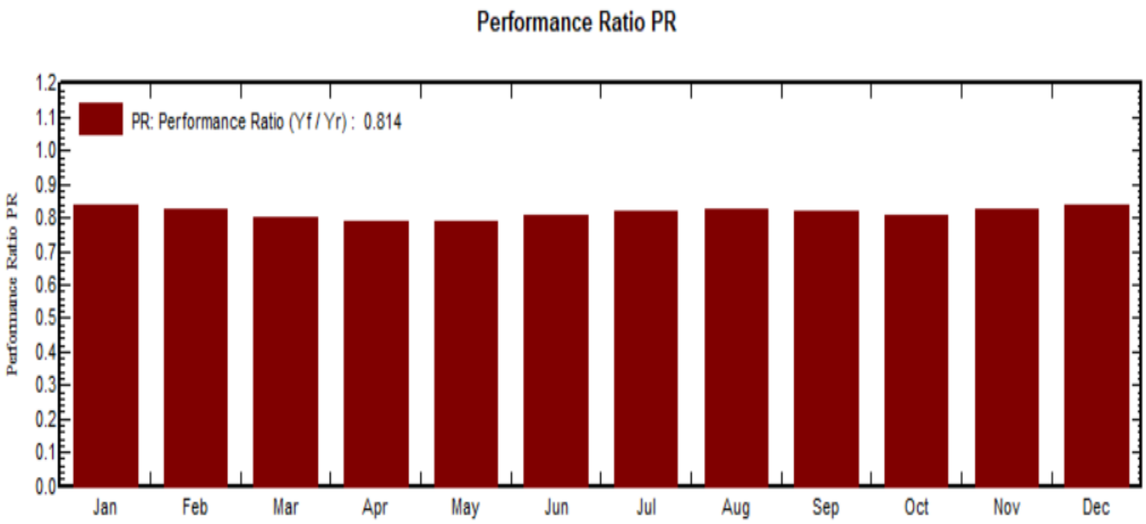

Figure 3. Performance Ratio for the Selected Location.

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HYBRIDIZATION OF WIND-SOLAR GENERATION – BENEFITS AND CHALLENGES:

Hybridizing the two power generation options, like wind and solar, will have several benefits as listed below.

1. Reliable Power Supply: Combines solar and wind to ensure availability under various weather conditions.
2. Energy Storage: Battery bank allows for a power supply during nighttime or calm/windless periods.
3. Efficient Energy Management: The Hybrid controller optimizes source usage and battery charging.
4. The system will have a superior reliability and reduced intermittency due to the complementary nature of wind-solar generation. Thus, it reduces the chances of power shortage or outage in almost any season or month of the year. Solar provides maximum power during sunny daytime hours, which often corresponds to low wind periods. Wind usually provides power during nighttime, cloudy weather, and winter months when solar output is absent or low. The combined system will also require a smaller battery bank as the two sources cover each other's gaps. This will significantly reduce the battery bank cost in comparison to the solar generation or wind generation alone.
5. As the system is off-grid, total independence from the utility grid is ensured. In the isolated and remote areas where it is difficult to make power reach by developing grids, it will be much easier to install these hybrid systems. This will also help the system to be free from grid-side issues like total power failures or government policies.
6. The complementary generation of solar wind increases the capacity utilization factor (CUF).
7. These generation options are environmentally friendly and almost net zero for reducing the carbon footprint.
8. Both wind turbines (which use scattered plots) and solar panels (which require flat surface area) can be co-located and share supporting infrastructure like access roads, power conditioning equipment, and control systems, leading to better utilization of land.
9. These systems can be incorporated for remote area applications like telecommunication towers, monitoring stations, or essential rural services.

CRITICAL CHALLENGES IN SOLAR-WIND HYBRIDIZATION:

The challenges include design complexity, component management, high initial costs, hybrid power control, and battery maintenance issues and related losses.
1. Problems with technology and design
• Optimal Sizing and Resource Variability: It is difficult to find the right size for solar panels, wind turbines, and the battery bank. Solar and wind power work well together (solar power is strongest during the day, while wind power peaks at night or in winter), but neither is always available, and they are hard to predict. If the system is too large, it costs a lot; if it is too small, it often runs out of power (Loss of Power Supply Probability - LPSP).
• Energy Management and Control System (EMS): An intelligent energy management system (EMS) is needed to handle power flows and decide which source supplies the load first. Choosing when to charge the battery and where to get power from is complicated. Preventing batteries from overcharging or deeply discharging (which shortens their lifespan) can also be a significant challenge.
• Quality and Stability of Power: The system must maintain a steady output voltage and frequency for sensitive loads, which is difficult because the input from solar and wind constantly varies.
• Site-Specific Constraints: Finding a location with both high solar irradiance and favorable wind patterns can be challenging.

2. ECONOMIC AND FINANCIAL CHALLENGES

• High Initial Capital Cost: The upfront expense of solar panels, wind turbines, power electronics, and especially the large battery bank is significantly higher than that of a grid-connected or single-source system.
• Cost and Lifespan of Batteries: Batteries are the costliest component and have the shortest lifespan, typically lasting 5–8 years.
• Maintenance and Logistics: Standalone systems are often located in hard-to-reach areas, making it difficult and costly to transport, install, and maintain them—particularly for the moving parts of wind turbines.

3. PROBLEMS WITH STORAGE (BATTERIES)

• Degradation and Cycling: The capacity of batteries decreases over time, and frequent, deep charge/discharge cycles standard in off-grid systems tend to shorten their lifespan.
• Thermal Management: Extreme temperatures (hot and cold) can significantly impact how well and how long batteries last. These conditions are common at remote installation sites.
• Safety and Monitoring: To prevent dangerous failures, batteries must be carefully monitored for their State of Charge (SoC) and State of Health (SoH), which pose additional challenges.

CONCLUSION:

The study explores the dynamic analysis of a small 2 kW solar power generation system located in Rajkot, Gujarat, India. It produces approximately 1653 kWh/kWp per year, with a normalized output of 4.53 kWh/kWp per day and a performance ratio of 0.814 or 81.4%. The paper also discusses the concept of solar-wind hybridization in standalone or off-grid mode, along with its benefits and challenges. Key advantages include system reliability, the complementary nature of power sources, and cleaner energy production, all examined in detail. Significant challenges involve system complexity, maintaining battery voltage, source prioritization, and battery maintenance issues, which are essential considerations for off-grid solar-wind hybrid systems.

ACKNOWLEDGMENTS:

The Gujarat Council on Science and Technology (GUJCOST), a state body in Gujarat that funds research in science and technology, sponsored this work in Gandhinagar, India. The grant reference number is GUJCOST/STI/2023-24/342. V.V.P. Engineering College in Rajkot, Gujarat, India, also supported this research.

AUTHOR CONTRIBUTION STATEMENT:

Both authors have contributed equally to the preparation of the manuscript.

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