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Climatic Impact on the Performance and Economics of Solar–Wind–Fuel Cell Hybrids in India

Santosh Uttamrao Bande[1], Dr. Sandeep Kumar Yadav[2]

[1]Research Scholar, Department of Mechanical Engineering,
Vikrant University, Gwalior, Madhya Pradesh 474006, India.
[2]Professor, Department of Mechanical Engineering,
Vikrant University, Gwalior, Madhya Pradesh 474006, India

ABSTRACT

Evaluating the technical performance and economic feasibility of solar–wind–fuel cell hybrid systems is increasingly vital to meet India's growing energy demands across diverse climates. Given India's geographical expanse, hybrid renewable systems leverage resource complementarity to deliver reliable and sustainable power, overcoming the intermittency inherent in standalone systems. In arid zones like Rajasthan, high solar irradiance provides optimal photovoltaic output despite limited wind. Conversely, coastal areas like Tamil Nadu and Gujarat benefit from strong wind corridors that offset reduced solar generation during monsoon cloud cover. In hilly or northeastern regions, resource variability makes efficient energy storage essential. Hydrogen-powered fuel cells play a critical stabilizing role by storing surplus power and generating electricity during low renewable output, thereby ensuring continuous supply and improved load management. Compared to standalone setups, hybrid configurations achieve higher capacity factors, superior resilience, and reduced power fluctuations. Advanced energy management systems further optimize resource utilization, making these systems especially valuable for remote and off-grid electrification where grid extension is impractical. Economically, hybrid systems carry high initial capital expenses for infrastructure installation. However, lifecycle analyses show that long-term benefits—such as minimal emissions, zero fuel costs, and low maintenance—outweigh upfront expenditures. Regions rich in solar and wind potential yield faster returns on investment, while supportive Indian government policies, subsidies, and incentives significantly improve economic viability. Ultimately, solar–wind–fuel cell hybrids offer a robust framework for decentralized energy. Adopting region-specific design and optimization will address existing cost and technical challenges, driving India's transition toward a clean and resilient energy future.

Keywords: *Solar–wind–fuel cell, Photovoltaic, PV, HOMER*

1. INTRODUCTION

Performance assessment and cost analysis of solar–wind–fuel cell hybrid systems play a crucial role in addressing India's growing energy demand while ensuring sustainability and energy security. India experiences a wide range of climatic conditions, including hot and arid deserts, humid coastal regions, mountainous terrains,

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and tropical zones, which significantly influence the performance of renewable energy systems. A hybrid energy system that integrates solar photovoltaic (PV) panels, wind turbines, and fuel cells offers a reliable and efficient solution by utilizing complementary energy sources and mitigating the intermittency associated with individual renewable technologies. The performance assessment of such systems focuses on evaluating energy output, system reliability, efficiency, and adaptability across different climatic regions of India.

Solar energy performance in India remains strong due to high solar irradiance levels, especially in regions such as Rajasthan, Gujarat, Madhya Pradesh, and parts of Maharashtra. Solar PV systems perform efficiently in these regions because of long sunshine hours and relatively low cloud cover. However, in coastal and humid regions like Kerala, Tamil Nadu, and West Bengal, higher temperatures and humidity affect PV efficiency by increasing thermal losses and reducing panel output. Performance assessment in these climates considers temperature coefficients, dust accumulation, and degradation rates. When solar systems operate alongside wind energy systems, overall system performance improves, as wind availability often increases during monsoon seasons when solar output decreases.

2. PROBLEM STATEMENT

The problem statement will address the growing challenges associated with meeting India's increasing energy demand while reducing dependence on fossil fuels and minimizing environmental impacts. India will continue to experience rapid population growth, urbanization, and industrial expansion, which will place significant pressure on existing power generation and distribution systems.

Conventional energy sources will contribute to greenhouse gas emissions, air pollution, and energy insecurity, particularly in regions with limited access to reliable electricity. These challenges will highlight the need for sustainable and resilient energy solutions that will perform efficiently under India's varied climatic conditions. The study will identify the limitations of standalone renewable energy systems, such as solar and wind, which will remain intermittent and climate-dependent. Seasonal variations, monsoon patterns, and regional climate differences will cause fluctuations in power generation, leading to reliability concerns. The lack of efficient energy storage and backup systems will further constrain renewable energy adoption, especially in remote and off-grid areas. Additionally, the high initial costs and technical complexities associated with hybrid systems will create uncertainties regarding their economic feasibility. This problem will necessitate a comprehensive assessment of solar–wind–fuel cell hybrid systems to evaluate their future performance, cost-effectiveness, and suitability for ensuring reliable, sustainable energy supply across India.

3. REVIEW OF LITERATURE

Several studies have emphasized that hybrid solar–wind systems significantly improve energy reliability by utilizing the complementary nature of these resources. Solar energy typically peaks during clear daytime conditions, whereas wind energy can be more prominent during evenings, nights, or monsoon seasons, especially in certain regions. This complementary behavior helps in maintaining a more balanced and consistent energy output throughout the year. Research findings indicate that hybrid systems reduce the dependency on a

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single energy source and enhance system efficiency, making them more suitable for regions with diverse environmental conditions.

The literature also highlights the importance of performance assessment in hybrid systems, focusing on parameters such as energy output, system efficiency, reliability, and capacity utilization. Advanced optimization techniques, including genetic algorithms and particle swarm optimization, have been widely used to improve system performance by determining the optimal combination of system components.

Studies show that well-optimized hybrid systems can achieve higher energy generation and better operational stability compared to standalone systems. Furthermore, simulation-based approaches have been extensively used to evaluate system behavior under different climatic conditions, enabling researchers to design systems tailored to specific geographical regions.

4. METHODOLOGY

In the first instance, the design and simulation of an HRES was carried out using five typical climate areas of India: hot and dry, warm and humid, moderate, composite, and cold. These regions were utilised to generate the HRES. In order to adequately account for geographical variation in solar radiation, wind potential, biomass availability, and other meteorological characteristics, five specific sites that are indicative of various climatic areas have been taken into consideration. A comprehensive comparison examination of the system's performance under a variety of environmental situations will be provided as a result of this.

In the second case, a solar photovoltaic (PV) rooftop facility that was installed on a university building in Delhi was simulated and modelled in order to evaluate the technological and economic feasibility of grid-connected renewable energy installation in a variety of climatic circumstances.

A hybrid setup that incorporates solar photovoltaics (PV), a biomass gasifier, and battery storage is used in the third case study. This system is modelled and analysed under composite meteorological circumstances. In this particular instance, a comprehensive analysis of the synergistic ability of hybrid systems to accomplish energy generation that is dependable, low-emission, and cost-efficient is offered.

The research will present an integrated picture regarding the technical design, economic feasibility, and environmental acceptability of hybrid renewable energy systems in India's primary climatic regions, thereby achieving the primary objectives that were stated earlier. This will be accomplished by combining the results of these three cases.

Given the findings of the literature review, it was determined that HOMER is an appropriate tool for conducting the techno-economic and environmental analysis of HRES. The HOMER software has the capability to model grid-connected and off-grid systems that are capable of satisfying both electric and thermal requirements. These systems may be constructed using a wide variety of photovoltaic modules, wind turbines, small hydro, biomass power, fuel cells, batteries, and hydrogen storage. Studying and developing these systems may be difficult due to the multiple design possibilities that are available as well as the uncertainty that surrounds critical elements such as load size and fuel price in the future. Additional complications are added to the situation by the fact that renewable energy sources are intermittent, seasonal, nondispatchable, and unclear in their supply. The HOMER system was designed in order to overcome these concerns.

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The simulation, optimisation, and sensitivity analysis are the primary functions that HOMER is responsible for doing.

In the process of simulating the functioning of a specific hybrid renewable energy system, HOMER generates the most optimally optimised outcomes that are achievable.

For the purpose of conducting a comprehensive analysis of the three distinct situations that are presented below, the methodology has been developed. (i) Design and comparison of HRES for five main climatic zones of India. ii) A technological and economic evaluation of a solar photovoltaic rooftop system that is linked to the grid in a composite climate zone?

(iii) Evaluation of a hybrid PV-biomass-battery system for cost-effectiveness, reliability, and emission reduction for composite climatic zone.

S. No	Station	Zone	Latitude (N)	Longitude (E)	Altitude (m)
1.	New Delhi	Composite	28.6429°	77.2191°	273
2.	Bangalore	Temperate	12.9716°	77.5946°	921
3.	Srinagar	Cold	34.0837°	74.7973°	1585
4.	Kolkata	Warm and Humid	22.5726°	88.3639°	5
5.	Jodhpur	Hot and Dry	26.23°	73.02°	217

Table 4. 1 Five selected stations of different climatic zones of India

S. No.	Station	Annual average solar radiation (kWh/m2/day)	Annual average wind speed (m/s)	Daily Temperature (°C)
1	New Delhi	5.06	4.55	25.61
2	Bangalore	5.26	5.54	24.00
3	Srinagar	4.63	2.41	07.65
4	Kolkata	4.67	4.65	25.92
5	Jodhpur	5.21	5.26	26.65

Table 4. 2 Potential of solar radiation and wind speed of different selected stations

S. No.	Component	Rated power (kW)	Lifespan	Capital cost (US$)	Replacement cost (US$)	Maintenance cost (US$)
1.	PV module	100, 200	25 years	3000	3000	10 $/year
2.	Wind turbine	3	20 years	18000	18000	180 $/year
3.	Electrolyzer	60	15 years	2000	2000	-
4.	Converter	60, 100	15 years	300	300	-
5.	Fuel cell	100	40,000 hours	3000	3000	0.10 $/op.hr
6.	Hydrogen tank	50 kg	25 years	1500	1500	-

Table 4. 3 Technical specifications and economic parameters of the proposed HRES

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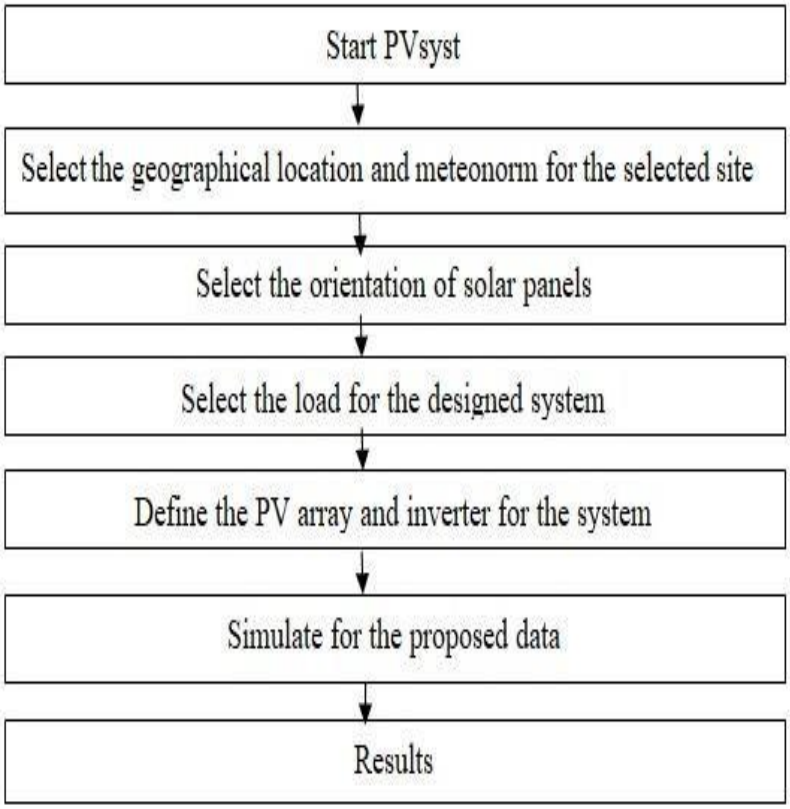


Figure 4. 1 Flowchart of simulation in PVsyst

5. RESULT AND DISCUSSION

Power output of components

Simulation has been carried out with the assistance of the HOMER program, taking into consideration the input parameters and restrictions that were discussed before. In accordance with the total number of non-player characters (NPC) and the power requirements that are required for a particular station within the context of its current energy resources, HOMER Pro simulates the available resources in accordance with the various stations that have been picked, as well as every system layout in the search space, and evaluates the ones that are more viable.

Validation of the proposed system results with previous published papers

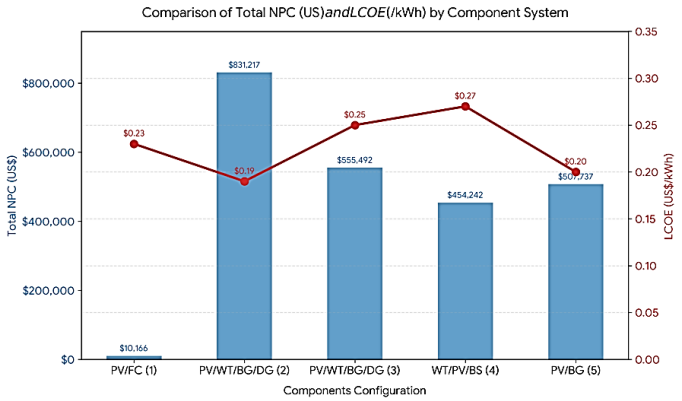
us research in that it utilises renewable resources and has various component sizes, load requirements, and utilisation of renewable resources. Because of this, it is not feasible to make an exact comparison between those systems. On the other hand, a comparison that is created on the basis of the economic designs of the systems might be regarded reasonable and suitable. Table 5.15 presents the results of a comparison between the NPC and COE of this suggested system with the findings of research that has been published in earlier studies.

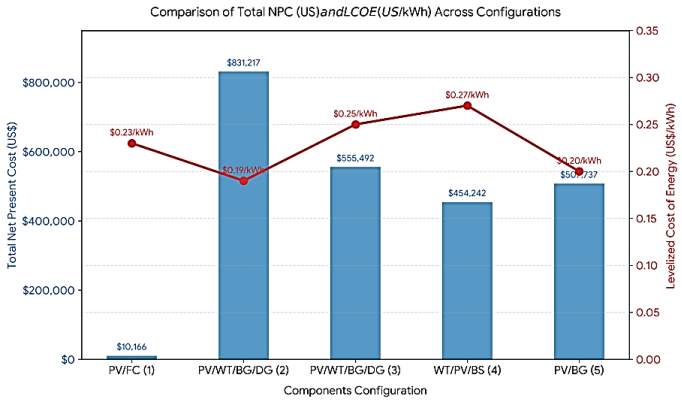
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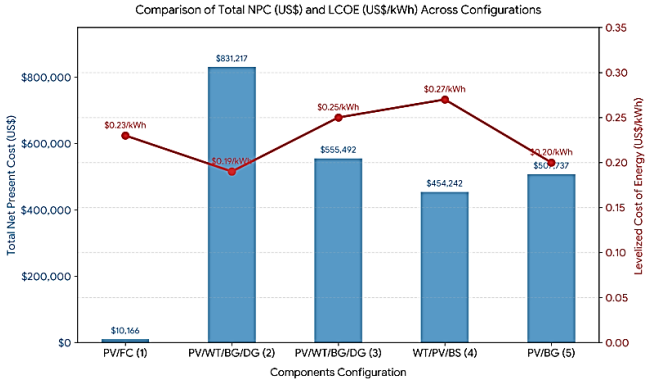
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S.No.	Components	Total NPC (US$)	LCOE (US$/kWh)
1	PV/FC	10,166	0.23
2	PV/WT/BG/DG	8,31,217	0.19
3	PV/WT/BG/DG	5,55,492	0.25
4	WT/PV/BS	4,54,242	0.27
5	PV/BG	5,07,737	0.20

Table 5.1 Various hybrid power configurations using HOMER







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6. CONCLUSION

The study on the performance assessment and cost analysis of solar–wind–fuel cell hybrid systems provides a comprehensive understanding of their feasibility and effectiveness in addressing the energy demands of a climatically diverse country like India. The overall conclusion drawn from the research highlights that hybrid renewable energy systems (HRES) are not only technically viable but also economically and environmentally sustainable when properly designed according to regional climatic conditions. The integration of solar photovoltaic systems, wind turbines, and fuel cell technologies successfully overcomes the inherent limitations of individual renewable sources, such as intermittency and unpredictability. By combining these resources, hybrid systems ensure a more stable and continuous energy supply, making them highly suitable for both grid-connected and off-grid applications across different parts of the country.

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