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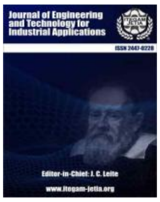

RESEARCH ARTICLE OPEN ACCESS

TECHNO-ECONOMIC ASSESSMENT OF HYBRID RENEWABLE ENERGY SYSTEMS FOR SUSTAINABLE ENERGY SUPPLY

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ABSTRACT

This study investigates the feasibility of a Hybrid Renewable Energy System (HRES) as a sustainable and cost-effective solution for rural electrification in regions of India with limited grid access. The research focuses on identifying the optimal hybrid configuration and conducting a pre-feasibility techno-economic analysis for supplying reliable electricity to an engineering institution located in Avalahalli, Bengaluru, Karnataka (560049). The proposed HRES integrates multiple renewable sources and was modelled and optimized using HOMER Pro software. Simulation results indicate that the most economically viable configuration achieves the lowest Net Present Cost (NPC) and Levelized Cost of Energy (COE), along with a 100% Renewable Energy Fraction (REF). The optimal design comprises 6170 kW of photovoltaic (PV) arrays, a 93 kW G10 wind turbine, 28,780 batteries (83.4 Ah each), and 761 kW power converters, yielding a COE of $0.388/kWh, a minimum NPC of $44.1 million, and only 4.16% unmet load. The system effectively meets the daily energy demands of 22,644 kWh (DC) and 2,508 kWh (AC) while achieving zero carbon emissions. Moreover, the HRES demonstrates strong economic performance with a payback period of 3.61 years, a return on investment of 34.8%, and an interest rate of 39.8%, confirming its viability for rural electrification.

I. INTRODUCTION

It Rural development is heavily reliant on access to electricity, especially in developing countries like India. Reliable electricity is critical to fostering economic growth, creating jobs, alleviating poverty, and enhancing the quality of life in rural communities. However, many remote rural communities experience frequent power interruptions, poor power quality, and limited access to the central grid due to their geographic isolation. Extending the utility grid to these areas is often economically unviable, primarily due to high infrastructure costs and low anticipated returns on investment. To address the constraints of rural electrification, decentralized power generation and freestanding renewable energy systems, such as photovoltaic (PV) and wind-based technologies, are increasingly being used to meet localized energy demands. Among these, hybrid renewable energy systems (HRES), which integrate several energy sources, have emerged as a feasible solution.

HRES provide greater reliability, sustainability, and cost-effectiveness, making them ideal for electrifying remote and isolated rural areas. The implementation of HRES in both rural and urban areas has the potential to increase electricity availability, reduce carbon emissions, boost economic development, and solve challenges related to fossil fuel depletion. Studies indicate that global warming could be mitigated by approximately 2°C per year through the adoption of low-carbon energy solutions [1]. Nevertheless, projections suggest that by 2030, carbon dioxide (CO_2) emissions from existing fossil-fuel-based energy systems will account for nearly 20% of global energy-related CO_2 emissions [2]. Additional factors driving the shift away from fossil fuels include the continuous decline of conventional energy resources and the rising global energy demand [3].

In this context, renewable energy sources, characterized by their regenerative nature, zero emissions, and environmental sustainability, are expected to serve as the cornerstone of future energy generation systems [4]. Dependent predominantly on fossil fuels and nuclear energy, current electricity generation contributes significantly to environmental pollution. Extending the central grid to remote rural areas is often economically unviable, making the integration of renewable energy resources (RERs) such as PV, wind, and biomass with conventional systems a feasible alternative. However, the intermittent nature of renewables limits their reliability when operating standalone. Incorporating battery-based energy storage into HRES addresses this issue by balancing generation and demand variability, ensuring a stable, continuous power supply [5]. RERs have seen increasing global deployment in recent years due to the need for sustainable, environmentally friendly power generation.

India is among the leading nations in renewable energy development, with RERs contributing approximately 35.86% of its total power generation capacity. According to the Central Electricity Authority of India, the country aims to increase this share to 57% by 2027 [6]. According to the Central Electricity Authority's 2027 plan, India's energy mix is estimated to include 72 GW of hydroelectric power, 275 GW of other renewable energy sources, 15 GW of nuclear power, and an additional 100 GW of non-emission-based technologies [7]. During the 2019 United Nations Climate Summit, the government pledged to raise its renewable energy capacity target from 175 to 450 GW, underscoring its commitment to sustainable energy development [8], [9]. To achieve its revised 2022 renewable energy target of 227 GW, an increase from the initially proposed 175 GW, India plans to. The advantages of employing RERs over conventional fossil fuels for electricity generation have been well documented [10].

As evident from current trends, the energy sector is progressively transitioning towards RERs, with a specific focus on implementing HGIRES, which offer both environmental sustainability and economic feasibility. Consequently, RERs are increasingly recognized as a practical and efficient solution for electrifying remote and underserved rural areas [11]. In recent years, HGIRES, which integrate one or more RERs with energy storage systems, have emerged as a promising solution for electrifying remote and underserved regions, both in grid-connected and standalone modes [12]. Advancements in renewable energy technologies and power electronic converters have enabled the conversion of variable and intermittent RER outputs into stable, regulated power suitable for diverse electrical loads. The concept of utilizing RERs for decentralized electrification in isolated areas has gained significant traction due to their environmental benefits and widespread availability [13]. RERs not only offer environmental benefits by reducing carbon emissions but also ensure long-term sustainability through their renewable, locally available nature.

Furthermore, hybrid systems that combine multiple renewable sources enhance system reliability by providing a continuous, consistent power supply under varying environmental conditions [14]. The literature defines a variety of HRES setups that incorporate solar panels, biogas generators, diesel generators, wind turbines, hydro energy, and bio gasifiers, and are adapted to local resource availability [15]. These systems have been proposed to meet load demand continuously while using as few RERs as possible. When RER supply exceeds demand, the excess energy is stored in battery systems and then used during peak periods of low generation or for backup. Table 1 summarizes recent studies on the techno-economic evaluation of standalone HRES, mainly focusing on NPC, COE, and optimal system design. The authors of [16] used the HOMER software framework to examine an HRES for rural electrification. The optimal arrangement consists of PV, WT, DGs, and battery storage. The system has a COE of $0.338/kWh, an NPC of $3.45 million, and a 100% renewable energy percentage. It meets a daily demand of 2,589.69 kWh while supplying 70% of its energy from renewable sources.

In [17], the authors analyzed the wind energy potential at two locations, Aluru Kona and Ellutala, in the Anantapur district of Andhra Pradesh, using wind speed data collected at 10 meters above ground level between January 1 and February 1, 2019. The information was gathered from the MINES Paris Tech web domain. An empirical approach was used to estimate the Weibull distribution parameters (shape and scale) and the cumulative distribution function, facilitating the calculation of wind power density at both sites. These findings help determine the viability of wind energy deployment in areas with existing wind infrastructure. HOMER pro software is widely used for HRES design by optimizing configurations based on resource availability and techno-economic performance. An ideal HRES ensures a high renewable energy fraction, zero unmet load, and minimal NPC and COE, making it suitable for rural electrification. Literature indicates PV/DG/battery and WT/DG/battery systems are effective in regions with abundant solar or wind potential, with COE ($0.054/kWh-$0.588/kWh).

Table 1: Summarizes the latest review on the optimized design and technical and economic analysis of HGIRES.

Author/ year	Proposed optimal HRES model	Methodology	Design site and objective function	Findings and load type	Outcome
“P Harish Kumar, ” et.al., 2025 [18]	400kW-PV, 100kW-WT, 918 number of 12V batteries, 200kW converter, 100kW-electrolyzer, 200kW reformer, and 15kg hydrogen tank (H-tank)”.	HOMER Pro software	• Ahobilam village, India. • Latitude and longitude of 78°.71′ E and 15°.13′ N. • Minimizing NPC, attaining the least COE, and maximizing REF.	1. The Configuration accomplished the lowest NPC of $26.8M, a COE of $4.32/kWh, and a REF of 100 %. 2. Supplies reliable power and meets 94% of the daily load demand of 1,080 kWh/day.	HRES can supply 80% of the onsite electrical energy required to meet load demand, achieving 100% REF.
Reshma Gopi, R, et.al., 2024 [19]	“WT, electrolyzer, hydrogen tank, converter, and LL1500-W battery (4 units of 800 kW/	HOMER Pro software	• Billerahalli at “12°58.6′N latitude and 78°21.4′E longitude in Karnataka”.	The HRES offers a sustainable power to meet the load demand of 6752.83 kWh/day by utilizing 100 % RERs,	The proposed HRES is highly cost-effective, offering a short payback period of 3.75 years, a

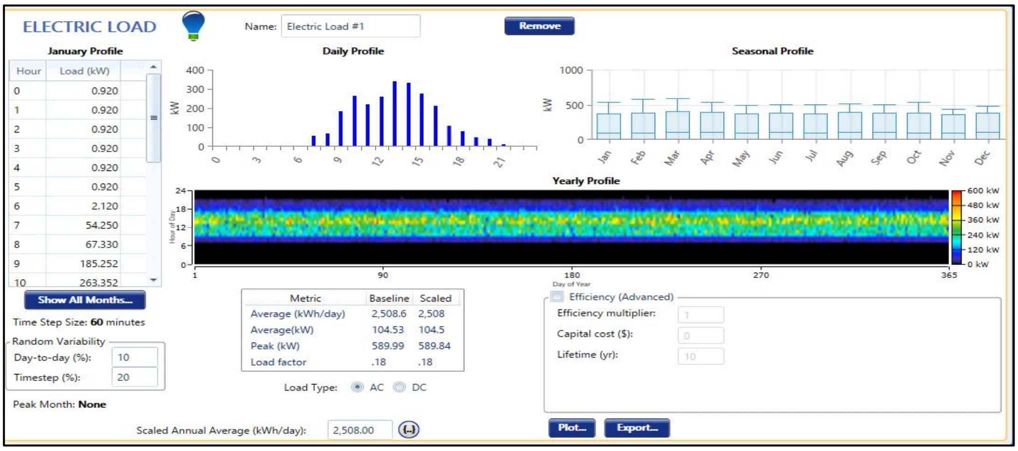
	100 kW/ 100 kg/ 734 kW/ 500 units)”.		• To design an optimal hybrid system design, considering parameter uncertainty.	with an NPC of $5.21M and a low COE of $0.25/kWh	35.0% rate of return, and a 37.4% interest rate.
Mohammad Toudefallah, Panagiotis Stathopoulos, 2024, [20]	“WTs, PVs, Batteries, Electrolyzers, FCs, and H2Ts”	Multi-objective genetic algorithm (MOGA)	Four scenarios (S1-S4) under minute-by-minute analysis comparing the LCOE, supply ratio, and profit. Among the scenarios, S4 shows the minimum COE of $0.4156/kWh, S2 achieves the highest supply ratio of 95.64% and the maximum profit of $13,565,610.	Tilos Island	MOGA outperformed MOPSO by completing calculations 6.5 times faster, while both algorithms produced comparable objective function values. Results illustrate trade-offs between cost-effectiveness, energy supply reliability, and profitability in hybrid energy system optimization.
Abirami, Manoharan, et.al., 2025, [21]	WT-50 kW, PV-120 kW, and geothermal-30 kW.	Simulation-based framework	The proposed HRES achieves energy and exergy efficiencies of 78.5% and 64.3%, respectively, while generating 500 kg of hydrogen per day at a low LCOE of $0.085/kWh. The energy contribution comes from geothermal (40%), wind (35%), and solar (25%) sources.	Solar irradiance (400-1000) W/m^2, wind speed (5-15) m/s, Geothermal heat flow (50-150) mW/m^2.	Optimization increases hydrogen production by 12% and provides a 6-year payback period, indicating strong scalability and economic potential.

Source: Authors, (2026).

This study applies HOMER to develop and evaluate optimal HGIRES configurations for Avalahalli, Bengaluru, with a focus on cost-effectiveness and environmental sustainability. Two distinct load profiles and six hybrid combinations are analyzed to ensure accurate techno-economic feasibility. The structure of this document is as follows: The thorough literature review of recent publications on the best design of various HRES is included in Section 1. The site's profile load and other details are covered in Section 2. This section also provides detailed information on the wind and solar resources available at the site under consideration. Here, the components and their costs for designing various HGIRES configurations are clearly described. Section 3 elaborates on the study of different HGIRES configurations regarding NPC and COE based on the simulation findings. This section identifies the best configuration. In this part, the cost of the components used to achieve the ideal design is clearly described. The techno-economic examination of the elements that comprise the optimal configuration is detailed in Section 4. Lastly, section 5 provides the work's conclusion.

II. SYSTEM DATA

The main engineering college building is located in the Avalahalli village community, Bengaluru, Karnataka 560049, India, and has been considered in this work. It is situated at an elevation of 877 meters above sea level. It has a latitude and longitude of 13.25°N, 77.75°E. Numerous loads, including lights, fans, projectors, computers, printers, scanners, and air conditioners, are installed in the main block. To fulfil the growing load demand and provide a dependable power supply, an HRES must be constructed at this location. An onsite field survey was conducted to estimate the village's load demand over 24 hours. The collected load data were given as input to the HOMER software load module, with the scaled annual average (kWh/day) set as the 100% baseline, and 8,760 hourly load data values for the year were simulated using hourly load profiles and applied random variability factors table 2 present the surveyed load data, indicating peak demand during morning and evening hours. Load #1 (AC) showed a peak of 589.84 kW and 2,508.00 kWh/day, and Load #2 (DC) reached 2,874.2 kW and 22,644.0 kWh/day. Figures 1a and 1b illustrate the AC and DC load profiles across daily, seasonal, and annual scales.



Name: Electric Load #1

January Profile

Hour	Load (kW)
0	0.920
1	0.920
2	0.920
3	0.920
4	0.920
5	0.920
6	2.120
7	54.250
8	67.330
9	185.252
10	263.352

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): 10
Timestep (%): 20

Peak Month: **None**

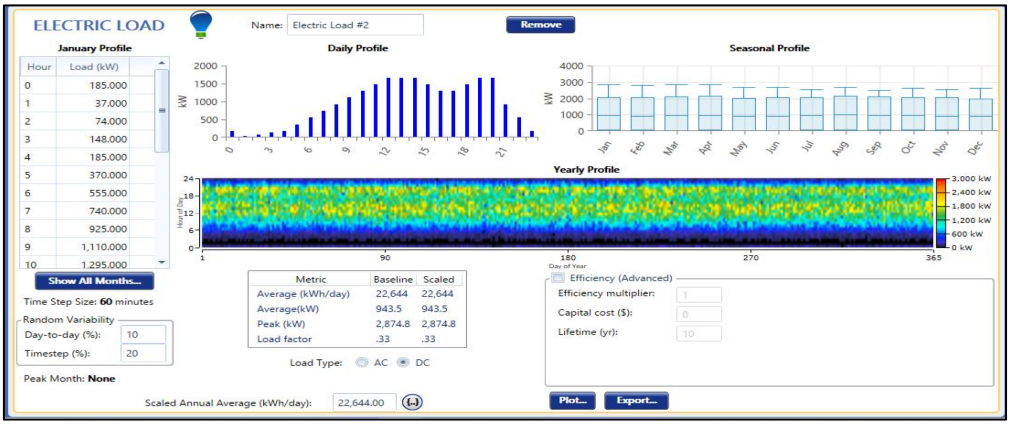
Metric	Baseline	Scaled
Average (kWh/day)	2,508.6	2,508
Average(kW)	104.53	104.5
Peak (kW)	589.99	589.84
Load factor	.18	.18

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost ($): 0
Lifetime (yr): 10

Scaled Annual Average (kWh/day): 2,508.00

Figure 1(a): Daily, seasonal, and yearly profile of AC loads.
Source: Authors, (2026).



Name: Electric Load #2

January Profile

Hour	Load (kW)
0	185.000
1	37.000
2	74.000
3	148.000
4	185.000
5	370.000
6	555.000
7	740.000
8	925.000
9	1,110.000
10	1,295.000

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): 10
Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/day)	22,644	22,644
Average(kW)	943.5	943.5
Peak (kW)	2,874.8	2,874.8
Load factor	.33	.33

Load Type: ○ AC ● DC

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost ($): 0
Lifetime (yr): 10

Scaled Annual Average (kWh/day): 22,644.00

Figure 1(b): Daily, seasonal, and yearly profile of commercial DC loads Data.
Source: Authors, (2026).

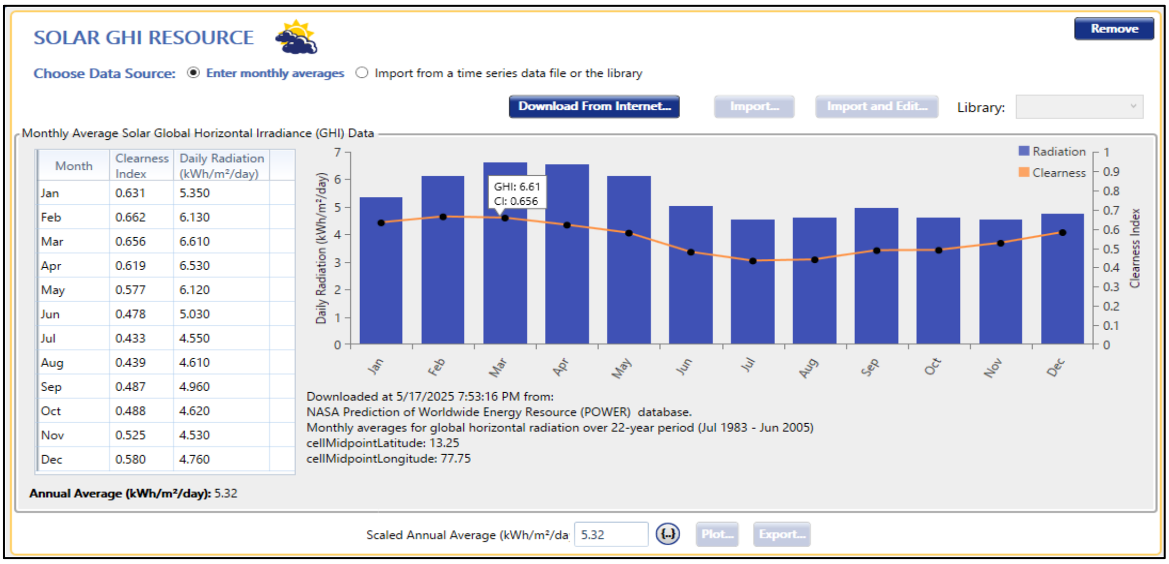
Table 2: Load demand at the considered site for 24-hour time period.

TIME	Ather EV bike (3.7 kWh) ELECTRIC LOAD 2	ELECTRIC LOAD 1
	Power consumption for one day (kWh/day)	Power consumption for one day (kWh/day)
01:00	37	0.9202
02:00	74	0.9202
03:00	148	0.9202
04:00	185	0.9202
05:00	370	0.9202
06:00	555	2.1202
07:00	740	54.2502
08:00	925	67.3302
09:00	1110	185.252
10:00	1295	263.352
11:00	1480	219.648
12:00	1665	259.962
13:00	1665	341.102
14:00	1665	330.276
15:00	1480	276.944
16:00	1295	213.458
17:00	1295	109.348
18:00	1480	80.9262
19:00	1665	46.9902
20:00	1665	39.0422
21:00	925	10.2722
22:00	555	1.9122
23:00	185	0.9202
00:00	185	0.9202
Power consumption for 24 hours in kWh	22644	2508.63

Source: Authors, (2026).

II.1 RESOURCE ASSESSMENT

RERs such as solar and wind are primarily considered for the development of the HRES in this assessment. At the selected site, solar radiation is available for approximately 10 to 12 hours per day during the summer months, decreasing to 6 to 8 hours in winter. The region experiences a peak summer temperature of 38 °C. NASA's Surface Meteorology and Solar Energy Database and NREL provide Solar irradiation data. Figure 2 presents the average monthly solar radiation and clearness index (CI), calculated over 22 years. The mean monthly solar radiation is 5.32 kWh/m²/day. At the same time, the CI, which quantifies atmospheric transparency on a scale of 0 to 1, has an annual average of 0.588, ranging from a maximum of 0.662 in February to a minimum of 0.433 in July.



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Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.631	5.350
Feb	0.662	6.130
Mar	0.656	6.610
Apr	0.619	6.530
May	0.577	6.120
Jun	0.478	5.030
Jul	0.433	4.550
Aug	0.439	4.610
Sep	0.487	4.960
Oct	0.488	4.620
Nov	0.525	4.530
Dec	0.580	4.760

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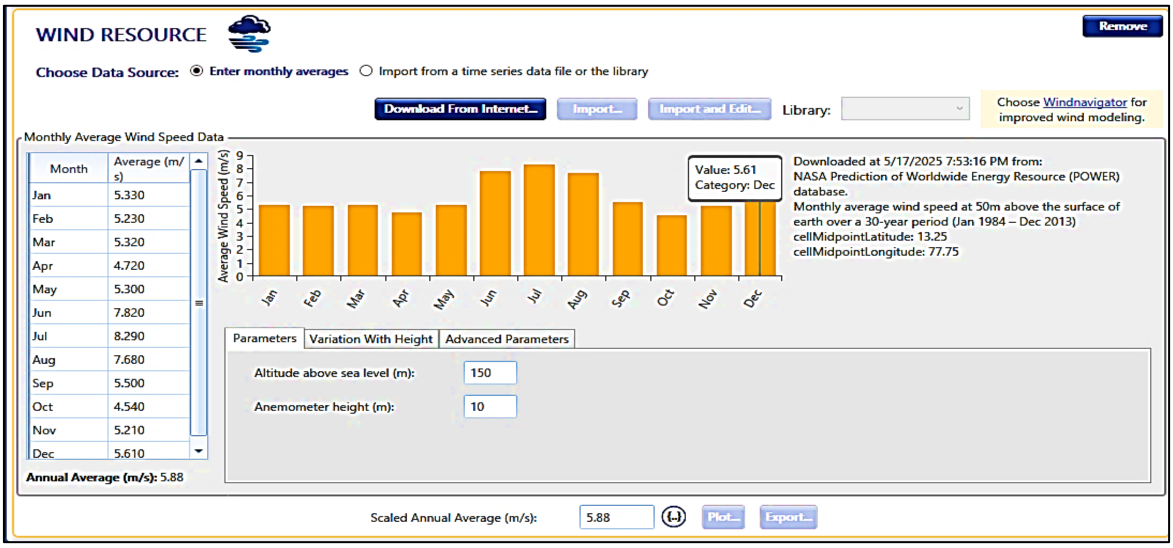
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly averages for global horizontal radiation over 22-year period (Jul 1983 - Jun 2005)
cellMidpointLatitude: 13.25
cellMidpointLongitude: 77.75

Annual Average (kWh/m²/day): 5.32

Scaled Annual Average (kWh/m²/da 5.32

Figure 2: Clearness index values and average monthly solar radiation data for the considered site.
Source: Authors, (2026).

Wind energy source: The mean monthly wind speed at 100 m over a decade at the study site is 4.89 m/s, with an annual average of 5.88 m/s and a surface roughness of 0.01. Figure 3 illustrates the monthly wind speed variation. Sensitivity analysis is used to evaluate the impact of wind speed fluctuations on system performance.



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Month	Average (m/s)
Jan	5.330
Feb	5.230
Mar	5.320
Apr	4.720
May	5.300
Jun	7.820
Jul	8.290
Aug	7.680
Sep	5.500
Oct	4.540
Nov	5.210
Dec	5.610

Annual Average (m/s): 5.88

Downloaded at 5/17/2025 7:53:16 PM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly average wind speed at 50m above the surface of earth over a 30-year period (Jan 1984 – Dec 2013)
cellMidpointLatitude: 13.25
cellMidpointLongitude: 77.75

Altitude above sea level (m): 150
Anemometer height (m): 10

Scaled Annual Average (m/s): 5.88

Figure 3: Monthly average wind speed data.
Source: Authors, (2026).

II.1I HRES AND ITS COMPONENTS

The HRES configuration architecture developed in this work comprises PV arrays, wind turbines, batteries, a converter, a diesel generator, and electrical loads. The integration of multiple RERs enhances system performance, reliability, and operational efficiency. Figure 4 illustrates the HGIRES configuration, designed based on site-specific demand data, resource availability, component specifications, and cost parameters. HOMER performs annual energy balance simulations to analyze system operation and calculate energy flows between HGIRES components. It schedules the operation of solar, wind, and DG sources, as well as battery charging/discharging. Multiple configurations are generated and evaluated to identify the optimal setup that meets load requirements. A techno-economic analysis is conducted for each component, considering capital, operating, fuel, maintenance, replacement, NPC, COE, REF, and CO_2 emissions. The analysis assumes a 25-year project lifespan, with an interest rate of 10% and an inflation rate of 3%.

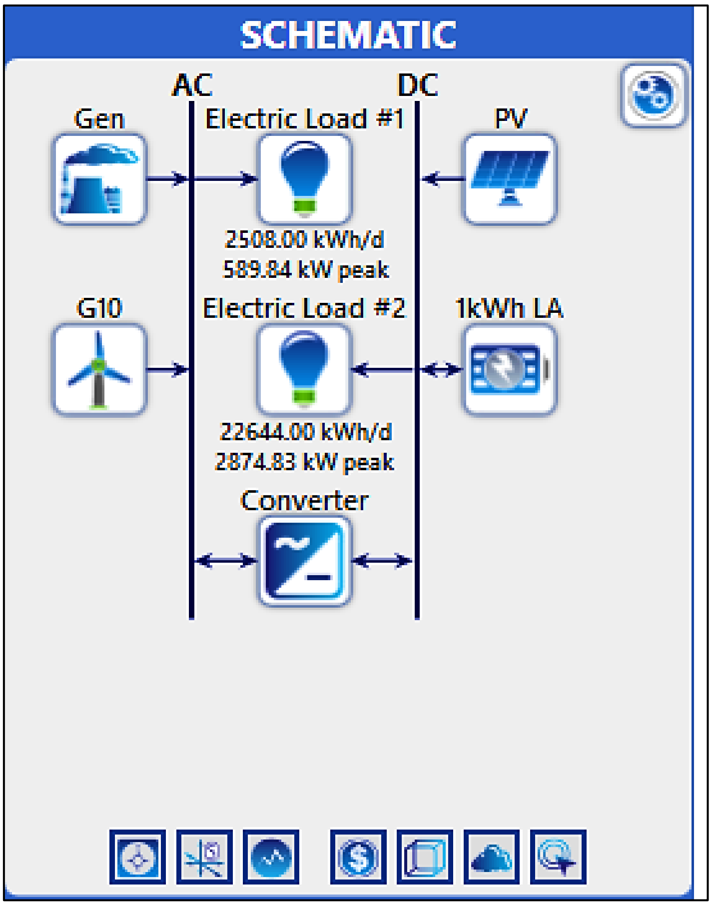


Figure 4: Schematic representation of the architecture of HGIRES.
Source: Authors, (2026).

The economic and technical specifications of the RES and components employed in this grid-integrated HRES design are provided in Table 3. The overall lifespan of the planned grid-integrated HRES system can be anticipated to be 25 years when applied to the location under consideration.

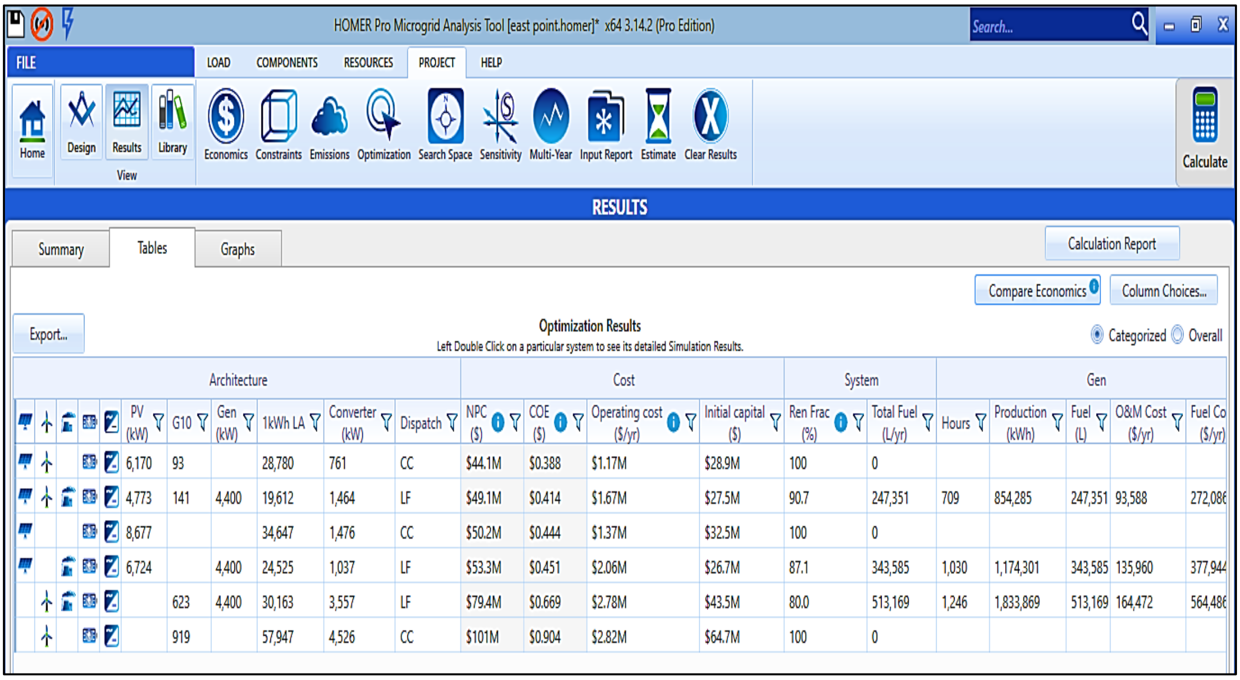
Table 3:Techno: Techno-economic details of Generic Flat Plate PV Module [22]/Wind Turbine (Generic 10 kW) [23]/ Battery (Generic 1kWh Lead Acid) [24], [25]/Generic system converter [26] as per US market price.

Parameter	**PV Module**	**Wind Turbine**	**Battery**	**Converter**
Component Name	Generic Flat Plate PV	Generic 10 kW Wind Turbine	Generic 1 kWh Lead-Acid Battery	Generic System Converter
Manufacturer	Generic	Generic	Generic	–
Rated Capacity	1 kW	10 kW	1 kWh	1 kW
Capital Cost	$2,500/kW	$50,000	$300	$300
Replacement Cost	$2,500/kW	$50,000	$300	$300
O&M Cost / Year	$10	$500	$10	$50
Lifetime (Years)	25	25	10	25
Efficiency (%)	80 (Derating Factor)	–	80	95

Source: Authors, (2026).

III. SIMULATION RESULTS AND DISCUSSION

This section provides a concise techno-economic evaluation of the proposed grid-integrated HRES using HOMER software. Simulations were conducted for multiple system configurations, depending on the selected component specifications, costs, and constraints. The optimization process identified the most efficient configuration with the minimum NPC and COE and the highest REF contribution, as shown in Figure 5. The optimal HGIRES configuration, comprising PV, WT, Batteries, and Converters, is illustrated in Figure 5. This configuration achieves a minimum estimated NPC of $44.1 million and COE of $0.388, and a REF of 100%. It includes 6,170 kW of generic flat-plate PV arrays, 93 units of 10 kW wind turbines, 28,780 units of 12 V batteries, and 761 kW of power converters. A filtered analysis of all simulation results, ranking configurations with the lowest NPC and COE, is summarized in Table 4.



Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture						Cost				System		Gen				
PV (kW)	G10	Gen (kW)	1kWh LA	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Co ($/yr)
6,170	93		28,780	761	CC	$44.1M	$0.388	$1.17M	$28.9M	100	0					
4,773	141	4,400	19,612	1,464	LF	$49.1M	$0.414	$1.67M	$27.5M	90.7	247,351	709	854,285	247,351	93,588	272,086
8,677			34,647	1,476	CC	$50.2M	$0.444	$1.37M	$32.5M	100	0					
6,724		4,400	24,525	1,037	LF	$53.3M	$0.451	$2.06M	$26.7M	87.1	343,585	1,030	1,174,301	343,585	135,960	377,944
	623	4,400	30,163	3,557	LF	$79.4M	$0.669	$2.78M	$43.5M	80.0	513,169	1,246	1,833,869	513,169	164,472	564,486
	919		57,947	4,526	CC	$101M	$0.904	$2.82M	$64.7M	100	0					

Figure 5: The optimized outcomes of the different frameworks of HGIRES.
Source: Authors, (2026).

Table 4 provides a comprehensive cost assessment of various HRES designs, and economic performance of the proposed PV/WT/Battery/Converter system. The obtained COE values are as follows: $0.414/kWh for the PV/Battery/DG/WT, $0.444/kWh for the PV/Battery system, $0.451/kWh for the PV/ Battery/ DG system, $0.669/kWh for the Battery/ DG / WT system, and $0.904/kWh for the Battery/Wind Turbine system. The corresponding NPs are $49.1 million, $50.2 million, $53.3 million, $79.4 million, and $101 million, respectively. Fuel consumption varies across configurations, with the PV/ WT /Battery system operating with zero annual fuel usage. In contrast, the PV/Battery/DG/WT system consumes 247,351 liters/year, the PV/Battery/ DG system consumes 1,174,301 liters/year, and the Battery/ DG / WT system consumes 1,833,869 liters/year. Fully renewable configurations report no fuel consumption. These findings highlight the techno-economic and environmental advantages of the PV/WT/Battery configuration for sustainable HGIRES deployment.

Table 4: Comparative Analysis of Six System Configurations.

Scenario/ configurations	**PV (kW)**	**Wind energy G10 (10 kW)**	**Genset (kW)**	**12V Battery**	**Converter (kW)**	**NPC (M$ $)**	**COE ($)**	**Operating cost (M $/yr)**	**Initial capital (M $)**	**System /RF (%)**	**Total Fuel (L/yr)**
PV/ Battery/WT	**6,170**	**93**	**-**	**28,780**	**761**	**44.1**	**0.388**	**1.17**	**28.9**	**100**	**0**
PV/Battery/ DG /WT	4,773	141	4,400	19,612	1,464	49.1	0.414	1.67	27.5	90.7	247,351
PV/ Battery	8,677	-	-	34,647	1,476	50.2	0.444	2.37	32.5	100	0
PV/ Battery/DG	6,724		4,400	24,525	1,037	53.3	0.451	2.06	26.7	87.1	1,174,301
Battery/ DG/ WT	-	623	4,400	30,163	3,557	79.4	0.669	5.78	80.0	0	1,833,869
Battery/WT	-	919	-	57,047	4,526	101	0.904	2.82	100	0	0

Source: Authors, (2026).

III.1 SUMMARY OF OPTIMAL SYSTEM COMPONENT COST

The NPC of the components utilized in the proposed HGIRES, namely the generic WT of 10 kW, 1 kWh lead-acid battery, flat-plate PV array, and system converter, is summarized in Table 5, with all costs reported in USD. The individual NPC contributions are as follows: $5,898,125.70 for wind turbines, $21,182,081.55 for the battery system, $16,222,354.13 for the PV array, and $798,395.24 for the converter, leading to a total system NPC of $44,100,956.61. The system retains a salvage value of $2,865,620.31, which is deducted from the overall project cost. Notably, the PV system requires no replacements over its operational lifetime, whereas the battery system incurs the highest cost share, with significant replacement expenses totaling $10,839,484.01.

Table 5: Summary of the total NPC and annualized costs of each component of optimal HGIRES.

Total NPC						
Name	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic 10 kW Wind Turbine	$ 4,650,000.0	$1,482,454.18	$ 601,129.52	$0.00	$ 835,458.00	$ 5,898,125.70
Generic 1kWh Lead Acid Battery	$ 8,634,000.00	$10,839,484.01	$ 3,720,539.26	$0.00	$2,011,941.72	$21,182,081.55
Generic Flat Plate PV Array	$15,424,739.81	$0.00	$ 797,614.32	$0.00	$0.00	$ 16,222,354.13
System Converter	$ 228,177.64	$ 96,809.80	$ 491,628.38	$0.00	$ 18,220.58	$ 798,395.24
Total System	$28,936,917.46	$ 12,418,747.99	$ 5,610,911.48	$0.00	$ 2,865,620.31	$ 44,100,956.61
Annualized costs						
Generic 10 kW Wind Turbine	$ 359,697.86	$ 114,674.32	$ 46,500.00	$0.00	$ 64,626.33	$ 456,245.84
Generic 1kWh Lead Acid Battery	$ 667,877.70	$ 838,481.54	$ 287,800.00	$0.00	$ 155,632.50	$ 1,638,526.74
Generic Flat Plate PV Array	$ 1,193,171.15	$0.00	$ 61,698.96	$0.00	$50.00	$ 1,254,870.11
System Converter	$ 17,650.54	$ 7,488.66	$ 38,029.61	$0.00	$ 1,409.44	$ 61,759.37
System	$ 2,238,397.25	$ 960,644.52	$ 434,028.57	$0.00	$ 221,668.28	$ 3,411,402.06

Source: Authors, (2026).

III.1I ELECTRIC OVERVIEW OF THE MOST EFFICIENT HGIRES

Table 6 presents the annual power generation, consumption, excess electricity, and unmet load associated with the components of the optimal HGIRES configuration. The total annual power generation of the system is 11,970,208 kWh, with 18.0% (2,152,198 kWh) contributed by the generic wind turbine and 82.0% (9,818,010 kWh) supplied by the generic flat plate photovoltaic (PV) array. With no deferrable load considered in this scenario, the system can handle a total load of 8,798,879 kWh/year, which is split between AC primary loads at 900,374 kWh/year (10.2%) and DC primary loads at 7,898,505 kWh/year (89.8%). The system experiences 2,484,759 kWh of excess power annually despite its significant generation capacity, suggesting opportunities for load control improvements or storage augmentation. Furthermore, there is a capacity shortfall of 921,762 kWh/year and 381,601 kWh/year of unmet electric loads, indicating locations where additional system improvement or hybrid integration may improve dependability.

Table 6: Summary of electricity production, consumption, and excess and unmet demand of the components of HGIRES.

Excess and Unmet		
Quantity	Value	Units
Excess Electricity	2,484,759	kWh/yr
Unmet Electric Loads	381,601	kWh/yr
Capacity Shortage	921,762	kWh/yr
Production Summary		
Component	Production (kWh/yr)	Percent
Generic flat plate PV	9,818,010	82.0
Generic 10 kW	2,152,198	18.0
Total	11,970,208	100
Consumption Summary		
Component	Consumption (kWh/yr)	Percent
AC Primary Load	900,374	10.2
DC Primary Load	7,898,505	89.8
Deferrable Load	0	0
Total	8,798,879	100

Source: Authors, (2026).

IV. TECHNO-ECONOMIC ANALYSIS OF THE COMPONENTS OF OPTIMAL HGIRES

This section presents the technical and economic analysis of the individual components incorporated in the optimal HGIRES configuration. PV array derating factor of 88% was assumed in this study, in accordance with values reported in the literature and accounting for performance-reducing factors such as dust accumulation, shading, aging, and wiring losses. The HOMER simulation tool was used to assess the maximum power output and performance characteristics of the PV system based on technical and economic parameters. At the considered site, solar power generation typically initiates around 06:00 AM, increases with rising solar irradiance, and ceases by 06:00 PM. Table 7 compiles the electrical characteristics, statistical performance indicators, and energy production metrics of PV incorporated in the optimal HGIRES configuration. The PV array has an installed capacity of 6,170 kW, with an average output of 1,121 kW and a peak output of 6,049 kW, yielding a daily average energy production of 26,899 kWh. The system operates approximately 4,394 hours per year, producing 9,818,010 kWh of energy. The PV array exhibits a capacity factor of 18.2% and achieves a PV penetration rate of 107%, indicating a substantial contribution to the total electrical load. The economic viability of the PV system within the hybrid configuration is further supported by its Levelized Cost of Electricity (LCOE), calculated at $0.128/kWh.

Table 7: Generic flat plate PV array Electrical Summary, Statistics, and Output (kW).

Electrical Summary		
Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	6,049	kW
PV Penetration	107	%
Hours of Operation	4,394	hrs/yr
Levelized Cost	0.128	$/kWh
Statistics		
Rated Capacity	6,170	kW
Mean Output	1,121	kW
Mean Output	26,899	kWh/d
Capacity Factor	18.2	%
Total Production	9,818,010	kWh/yr

Source: Authors, (2026).

A thorough overview of the system converter's electrical performance for this hybrid setup is provided in Table 8, together with statistics, inverter output, and rectifier output. According to the most recent statistics, the inverter ran for 2,907 hours per year, producing 314,828 kWh and consuming 331,398 kWh, resulting in 16,570 kWh of annual energy losses. Likewise, during 4,878 hours of operation per year, the rectifier produced 1,175,609 kWh of energy from 1,237,483 kWh of input, with 61,874 kWh of losses. The rated capacity of the rectifier and inverter is 761 kW. The inverter's mean output is 35.9 kW, whereas the rectifier's is 134 kW. Both components have a minimum output of 0 kW, while the rectifier and inverter have maximum outputs of 761 kW and 581 kW, respectively. The inverter's capacity factor is 4.73%, whereas the rectifier's is 17.6%. These measurements demonstrate the need for bidirectional power conversion for optimal HGIRES operation and energy flow control.

Table 8: The system converter Electrical Summary, Statistics, Inverter Output, and Rectifier output (kW).

Electrical Summary			
Quantity	Inverter	Rectifier	Units
Hours of Operation	2,907	4,878	hrs/yr
Energy Out	314,828	1,175,609	kWh/yr
Energy In	331,398	1,237,483	kWh/yr
Losses	16,570	61,874	kWh/yr
Statistics			
Capacity	761	761	kW
Mean Output	35.9	134	kW
Minimum Output	0	0	kW
Maximum Output	581	761	kW
Capacity Factor	4.73	17.6	%

Source: Authors, (2026).

According to the data, the diesel generator delivers a maximum electrical output of 28.5 kW and generates 4,093 kWh annually. The generator operates for approximately 298 hours per year, with the shortest single start duration recorded at 54 hours. The total annual fuel consumption is 1,769 liters. The generator exhibits a capacity factor of 0.865% and an estimated operational lifespan of 50.3 years. Twenty-eight thousand seven hundred eighty batteries are used in this system; these batteries are arranged in a single-string parallel topology, creating 28,780 strings with a 12.0 V bus voltage. 3,101,782 kWh of energy were entered into the batteries annually, while 2,493,657 kWh were output. In addition to energy losses totalling 621,800 kWh annually, the system encountered a storage depletion of 13,675 kWh annually. There were 2,787,993 kWh of energy throughput every year. A storage wear cost of $0.419/kWh and an autonomy of 16.5 hours are critical operating metrics. The battery bank has a total nominal capacity of 28,803 kWh, of which 17,282 kWh are usable. An estimated 23,024,000 kWh of cumulative energy throughput is anticipated from the system over its lifetime. These metrics show how well the battery system performs in terms of energy storage and how dependable it is in the hybrid setup.

The electrical overview and performance indicators of the chosen wind turbine system can produce up to 930 kW of power, with a minimum output of 0 kW. The system runs for 7,574 hours a year and achieves a wind penetration of 23.4%. With a mean output of 246 kW and a total rated capacity of 930 kW, the wind turbine has a capacity factor of 26.4%. 2,152,198 kWh of energy are produced annually by the wind turbine, and the system's LCOE is $0.212/kWh. These numbers show how important the wind turbine is to the hybrid system, providing a dependable and affordable renewable energy source at the chosen location. The NPC serves as the primary economic indicator in the HOMER simulation for evaluating and ranking system configurations, with the LCOE and total annualized cost derived accordingly [27], [28]. Table 9 compares the economic performance of the baseline system and the optimized HGIRES configuration. The optimal system comprising 6,170 kW of PV arrays, 93 kW of diesel generators, 28,780 strings of 1 kWh lead-acid batteries, and 761 kW of power converters achieves an NPC of $44.1 million and an LCOE of $0.388/kWh. In contrast, the base case system records a higher NPC of $53.3 million and an LCOE of $0.451/kWh.

The proposed hybrid system also demonstrates strong financial metrics, including a 40% internal rate of return (IRR), 35% return on investment (ROI), and a payback period of 3.6 years, indicating superior economic viability and reduced operational costs compared to the conventional diesel-based configuration.

Table 9: Comparison of existing models and proposed HGIRES model.

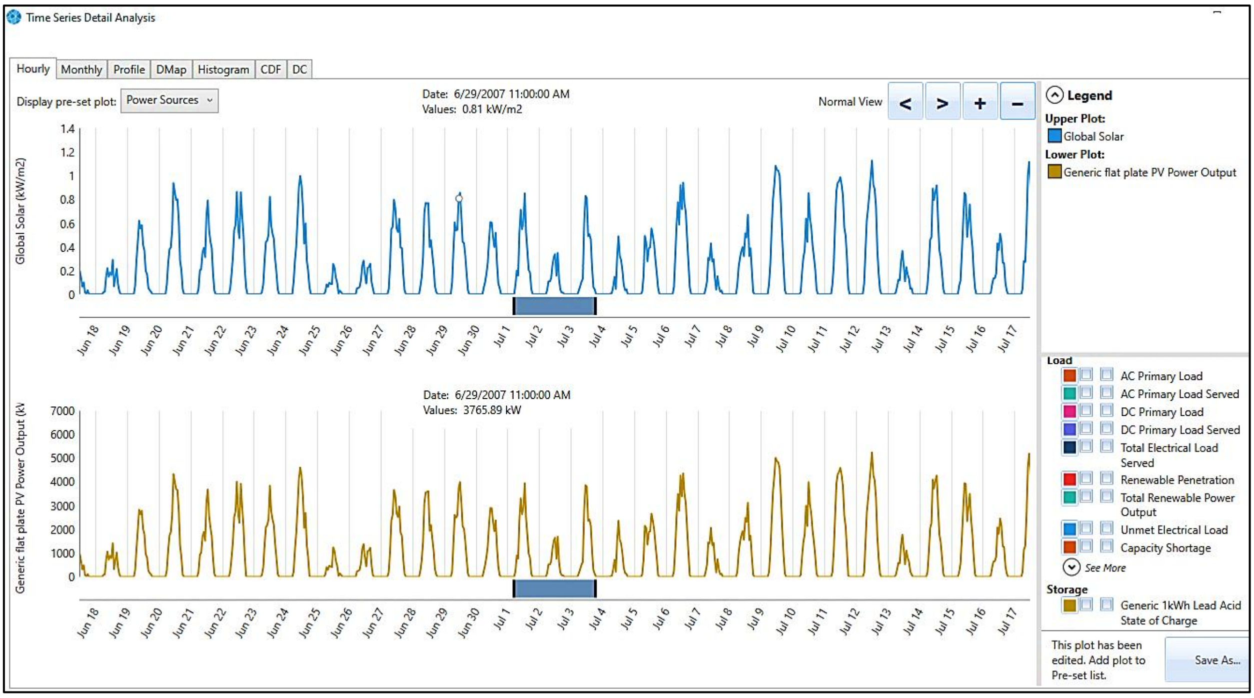
Parameters	Existing model			Proposed model
Optimal system	PV/DG/ Battery/ Conv. [29]	PV/DG/Battery/ Conv. [30]	PV/DG/Battery/ Conv. [31]	PV/WT/ Batt / CONV configuration
Solar irradiation (kWh/m^2/day)	4.56	4.864	3.96	5.32
Clearness index	0.51	0.540	0.57	0.588
Wind speed (m/s)	2.47	--	--	5.88
COE ($/kWh)	0.41	0.817	0.689	0.388
NPC ($)	903,092	1,849,654	11,707,000	44.1M
REF (%)	12	74	64	100

Source: Authors, (2026).

IV.1 TIME SERIES DETAIL ANALYSIS OUTPUT POWER WAVEFORMS OF THE VARIOUS SOURCES USED IN HRES

The software facilitates comprehensive time-series analysis to assess the temporal dynamics of power generation and consumption within the optimized HRES. It supports the simulation and optimization of integrated energy sources, including solar PV, WT, DGs, and battery storage systems. Figure 6 presents the time-series analysis of solar power generation for the optimized HRES configuration. The upper panel illustrates the global solar irradiance profile, which exhibits a typical diurnal pattern, with peak values reaching approximately 1.2 kW/m². On June 29, 2007, at 11:00 AM, the irradiance measured was 0.81 kW/m². The lower panel displays the corresponding power output of the generic flat-plate PV system, which closely follows the irradiance trend. During periods of high solar availability, the PV system achieved a peak output of 3765.89 kW. At 11:00 AM, consistent with the recorded irradiance, the PV system produced 3765.89 kW, indicating effective utilization of solar resources and strong system responsiveness. Figure 7 shows that the renewable power generation and corresponding energy supply to the electrical load by the optimized HRES configuration over a selected time period.

The total renewable power generated during this interval is 4,930.58 kW, with the peak load reaching approximately 3,000 kW. At 1:00 PM on August 28, 2007, the electrical demand was recorded at 2,765.57 kW. The plot highlights the interaction between renewable energy generation and load demand over a two-week period, revealing instances of surplus generation when supply exceeds demand. Such insights are critical for real-time monitoring and efficient operation of the HRES, ensuring a stable power supply and contributing to reduced energy costs. Figure 8 presents time-series plots of wind power data for the optimized HRES configuration based on the study parameters. The upper plot shows wind speed (m/s), with peak values reaching approximately 15.0 m/s, indicating strong wind resource availability. At 03:00 PM on June 23, 2007, the recorded wind speed was 14.47 m/s. Correspondingly, the lower plot displays the WT power output, which reached 874.73 kW at the same time. These results demonstrate the effective contribution of wind energy to the overall system performance under favorable wind conditions.



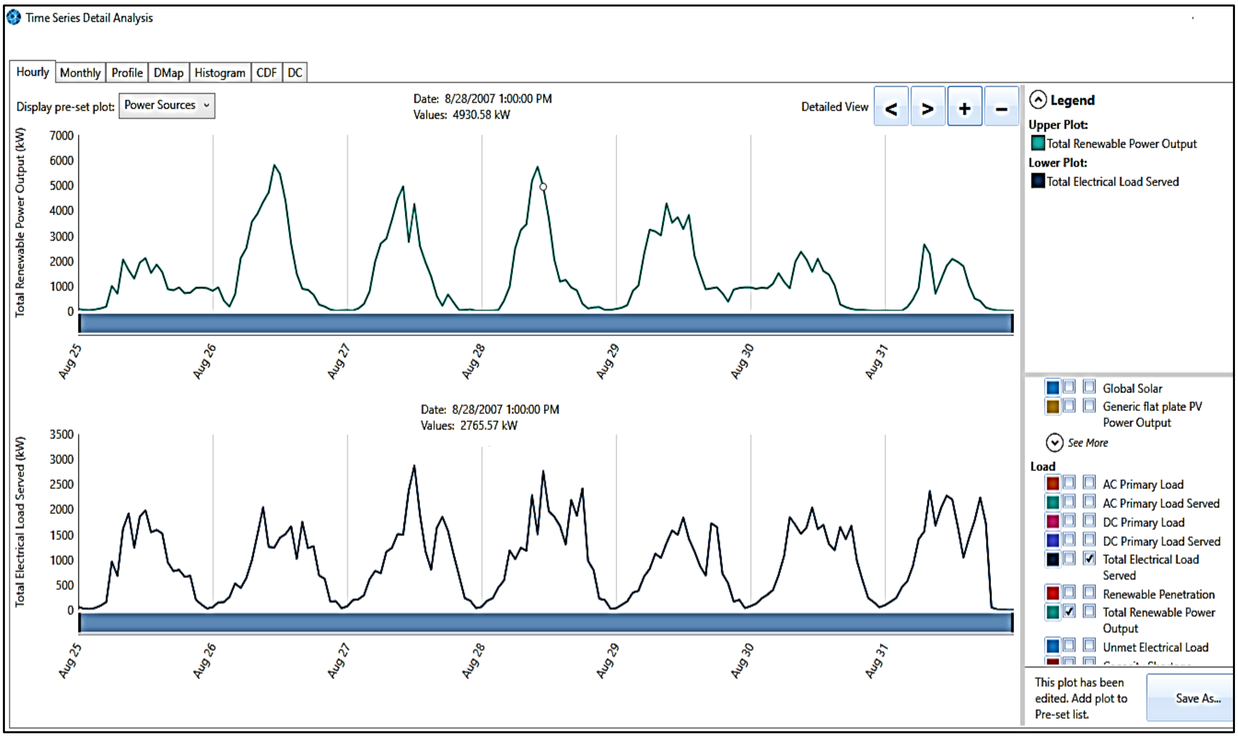
Display pre-set plot: Power Sources

Date: 6/29/2007 11:00:00 AM
Values: 0.81 kW/m2

Date: 6/29/2007 11:00:00 AM
Values: 3765.89 kW

This plot has been edited. Add plot to Pre-set list.

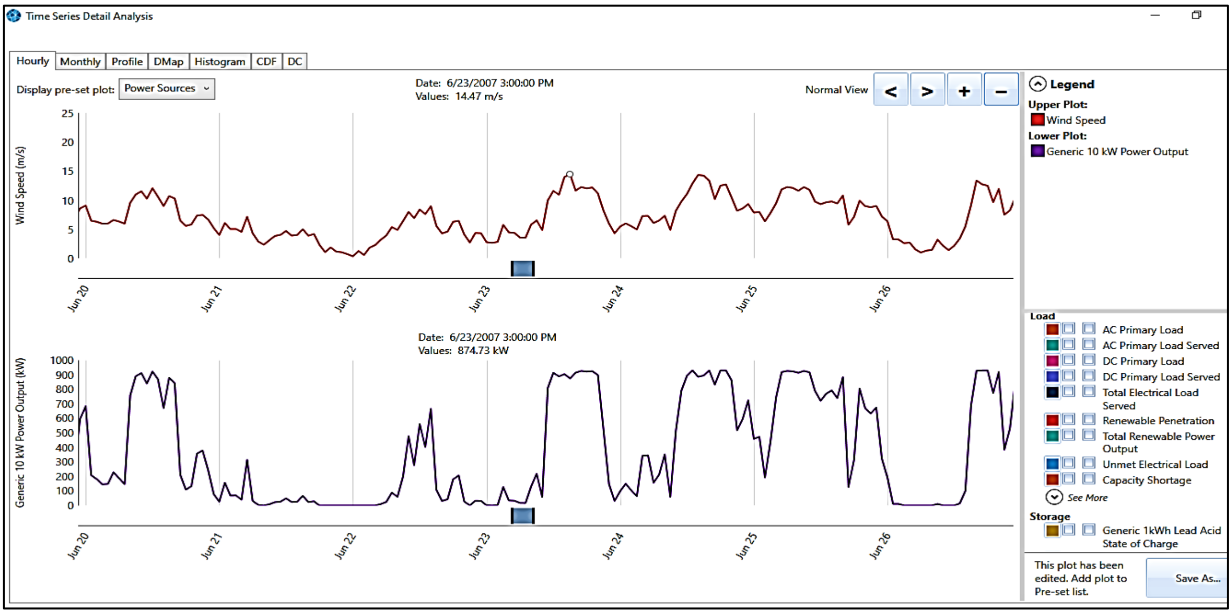
Figure 6: Total Power Output from PV Panels and Global Solar Irradiance for the Optimized HRES Desig.
Source: Authors, (2026).



Date: 8/28/2007 1:00:00 PM
Values: 4930.58 kW

Date: 8/28/2007 1:00:00 PM
Values: 2765.57 kW

Figure 7: Total Renewable Power Generation and Electrical Load Supplied by the Optimized HRES Design.
Source: Authors, (2026).



Date: 6/23/2007 3:00:00 PM
Values: 14.47 m/s

Date: 6/23/2007 3:00:00 PM
Values: 874.73 kW

Figure 8: Total Power Output from Wind Turbine and Wind Speed for the Optimized HRES Design.
Source: Authors, (2026).

V. CONCLUSIONS

This study presents a detailed techno-economic feasibility assessment and optimization of hybrid renewable energy systems (HRES) for rural electrification in Avalahalli, Bengaluru, Karnataka, India, considering site-specific solar irradiance, wind speed, and load demand characteristics. Six distinct hybrid configurations were modeled and analyzed using HOMER Pro to determine the most efficient and cost-effective design. Among the evaluated configurations, the PV/Wind Turbine (WT)/Battery/Converter system emerged as the optimal solution, effectively satisfying the daily electrical demand of 25,152 kWh with reliable, clean, and continuous power supply.

- The optimal configuration integrates 6170 kW of photovoltaic (PV) modules, a 93 kW G10 wind turbine, 28,780 batteries (83.4 Ah each), and 761 kW of power converters, achieving a 100% Renewable Energy Fraction (REF). It records the lowest Net Present Cost (NPC) of $44.1 million and a Levelized Cost of Energy (COE) of $0.388/kWh, while maintaining an unmet load of only 4.16%.
- The proposed system operates without fuel consumption, in contrast to the diesel generator (DG)-based system that requires 57,907 liters of fuel annually, leading to significant savings in operational costs and environmental impacts.

- From an environmental standpoint, the hybrid system reduces carbon dioxide emissions by 96.95%, producing only 3.05% of the emissions associated with the DG-only configuration. Economically, it demonstrates a short payback period of 3.61 years, a return on investment of 34.8%, and an interest rate of 39.8%, confirming its financial viability and sustainability for long-term deployment.

Furthermore, government incentives and subsidies for renewable energy projects could further enhance the affordability and implementation potential of such hybrid systems in remote and underserved regions. Promoting these systems would not only accelerate rural electrification but also contribute to India's clean energy transition, reduce dependency on fossil fuels, and stimulate local economic growth. Overall, the findings highlight that a properly designed hybrid renewable system can serve as a technically reliable, economically viable, and environmentally sustainable pathway toward achieving energy security and carbon neutrality in rural India.

VI. AUTHOR'S CONTRIBUTION

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