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POWER QUALITY ANALYSIS

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Abstract: In recent years, the demand for clean and reliable electricity in educational buildings has grown quickly and help to run educational building having low COE value. Present study focuses on designing and analyzing a Grid-Connected Hybrid Renewable Energy System (HRES) for an educational institute in Jaipur (India). The HRES system includes solar panels, wind turbines, battery energy storage, and conventional electrical generator, all connected to the main electricity grid. The goal is to provide a continuous, cost-effective, and eco-friendly power supply with good power quality. The current research was done in two stages. First, HOMER software was used to analyze different combinations of energy sources. The best solution was selected based on overall cost, fuel savings, and environmental benefits which was LCOE (levelized cost of electricity). The results of the present study showed that the optimal hybrid system had a Net Present Cost (NPC) of ₹172 million, Initial Capital of ₹89.1 million, Operation & Maintenance cost of ₹6.39 million per year, and a Levelized Cost of Energy (LCOE) of ₹5.72/kWh. These values are significantly better than the base case system (only grid purchased electricity), which had higher costs in all categories. In the second stage, Python-based modeling and control techniques were used to check how the system performs under different weather and load conditions. Special attention was given to maintaining stable voltage and frequency, and to reducing harmonic distortion (THD) for the protection of sensitive classroom and lab equipment. The battery's State of Charge (SOC) was managed using an adaptive control method to improve energy reliability. Current study shows that a hybrid system combining renewable sources with a grid connection can reduce both electricity bills and greenhouse gas emissions. It also improves the power quality and reliability for educational institutions, making it a strong solution for future energy needs in India and similar regions.

Keywords: HRES, Solar, Wind, Battery System, Power Quality, HOMER

1. Introduction

World's people numbers go up all the time, about 8.1 billion in 2023 and maybe over 9.7 billion by 2050⁴¹⁾ (United Nations, 2023). More people mean more need for energy to do things, grow industries, and build cities. India is now most populated country with over 1.42 billion people that use a lot of energy⁴²⁾ (World Bank, 2023). India's economy is growing fast; it needs steady energy supply as buildings and machines become more common. Many new gadgets, electric cars, and online services make electricity needs higher so it puts stress on power systems already there. International Energy Agency (IEA) says that India's demand for energy may double by year 2040 so must change power strategies now to keep things good.

Traditional methods for generating energy mainly using fossil fuels like coal or gas still provide most electricity everywhere but have big problems:

Environmental Issues: Burning fossil fuels adds lots of greenhouse gases causing climate effects.

Resource Problems: Fossil fuel sources are running low quickly making worries about energy safety.

Import Dependence: Places like India depend on oil imports which makes them sensitive to price changes and global issues.

Health Risks: Bad air from old power plants causes health troubles such as lung diseases.

Hybrid Renewable Energy Systems (HRES) show promise as an alternative to standard generation methods because they mix different renewable sources like solar or wind with older ways making reliable supplies easier while reducing pollution too. The Indian government aims for having renewable capacity of 500 GW by year end of decade highlighting importance of HRES shift⁴⁰⁾.

Still many rural areas in India don't get stable electricity—about 35 million lack access especially far-off places according to World Bank data. Extending traditional grids here often costs too much due geographical issues so HRES

offers better path using local renewables creating small self-sufficient mini-grids providing needed electrification. Solar panels plus batteries give constant power while cutting back on fossil fuel usage.

Power quality also matters with HRES ensuring stable electrical output without too many changes in voltage or frequency since bad quality can break equipment waste electricity hurt economy badly facing hurdles including:

Voltage Changes: Fluctuations due intermittent nature of renewables.

Harmonic Issues: Caused by inverter-related renewable setups.

Frequency Control: Affected when loads suddenly spike or drop leading extra challenges tackling these tough parts through advanced electronics studies grid stabilizing options known aids can help manage this situation improve overall effectiveness efficiency goals when building future solutions thus replacing outdated models completely. methods plus smart energy control systems mix into HRES. Clever inverters, FACTS (Flexible AC Transmission Systems), and ways to manage demand aid in controlling voltage levels, harmonics, and frequency changes. Microgrid designs enabled by HRES give a consistent and high-grade power supply for schools, factories, and homes.

As India's population grows plus energy needs increase, moving from regular energy sources to Hybrid Renewable Energy Systems is necessary. HRES not only solves the issues from fossil fuel generation but also helps rural electricity access, sustainable progress, and better power quality. The joining of solar, wind, battery backup, with traditional sources in an interconnected system provides energy safety, cost-effectiveness, alongside environmental care. Future studies and policies need to focus on improved energy management methods along with grid upgrades and smart monitoring tools to fully use the benefits of HRES for India's educational facilities along with rural power systems.

The novelty of current study was that it combines solar energy, wind energy, battery storage, and a conventional generator into one smart HRES system connected to the electricity grid, specially designed for an educational building in Jaipur, India. Unlike many previous works that only focus on cost or single energy sources, present study focuses on both cost-saving and power quality. It uses HOMER software for system design and Python-based control to keep the power supply stable and clean. It also checks how well the system works in real weather and load conditions. This combination of technical performance and power quality analysis in a real educational setup makes the study unique.

The main aim of current study was to design and test a grid-connected hybrid renewable energy system (HRES) that can give clean, reliable, and low-cost electricity to an educational building in Jaipur. The HRES system combines solar panels, wind turbines, batteries, and a backup generator to make sure power is always available. The study tries to lower electricity costs and pollution, find the best and most affordable setup using HOMER software, and improve power quality by controlling voltage, frequency, and harmonics through Python-based simulation. It also checks if the system works well during changes in weather and electricity use. This research hopes to help Indian schools and colleges use better, cheaper, and greener energy in the future.

2. Literature Review

Many researchers have worked on hybrid renewable energy systems (HRES) to improve power supply and reduce pollution. (Kumar et al. 2024)¹⁾ showed that HRES using solid waste energy can lower carbon emissions and improve energy savings. (Nadeem et al. 2024)²⁾ focused on off-grid HRES using solar and biomass to supply electricity in rural areas where the grid is not available. (Shaier et al. 2025)³⁾ developed a multi-objective optimization model combining solar, wind, and storage, which helped improve the overall system performance and energy efficiency. Similarly, (Vechalapu and Bhaskara Reddy 2024)⁴⁾ created a special controller using DC-DC converters to distribute energy effectively in microgrids.

(Bhimaraju and Mahesh 2024)⁵⁾ reviewed many studies and found that good system design is key to improving the performance of solar-wind systems. (Rathod and S 2024)⁶⁾ used an optimization algorithm to find the best HRES configuration for lower cost and less environmental impact. (Adefarati et al. 2025)⁷⁾ applied evolutionary algorithms to reduce the cost and improve the sustainability of HRES designs.

In recent years, advanced algorithms have helped improve HRES optimization. (Guvén et al. 2025)⁸⁾ used a unique method called Artificial Gorilla Troops Optimizer to improve system stability and reduce costs. (Kumar and Kumar 2024)⁹⁾ applied Fisher Swarm Optimization to hybrid systems in the Andaman and Nicobar Islands, helping in isolated power planning. (Campos et al. 2024)¹⁰⁾ performed a cost and eco-efficiency study of a biomass-solar system to guide cleaner energy use. (Amoussou et al. 2024)¹¹⁾ focused on improving solar-diesel-battery systems for better power in weak-grid areas.

Several researchers have also explored forecasting and local design. (Komanapalli et al. 2025)¹²⁾ studied how local weather affects the planning of hybrid systems in Northeast India. (Keyvandar and Saif 2024)¹³⁾ created an adaptive and flexible method to size hybrid systems accurately under uncertain conditions. (Bhagat and Anwer 2024)¹⁴⁾ designed hybrid power plants for Karnataka based on changing energy demand. (Adlinde et al. 2024)¹⁵⁾ used new converters to improve the reliability of microgrids powered by hybrid sources.

Power quality is also a growing research area. (Gurumoorthi et al. 2024)¹⁶⁾ used a hybrid deep learning model to improve energy flow and distribution in HRES, resulting in better performance. (Baghel et al. 2024)¹⁷⁾ studied how different weather zones in India affect hybrid systems. (Chiluka and Sekhar 2025)^{18, 20)} introduced a smart energy

management system with Z-source converters and control strategies to improve energy output and efficiency.

(Saharia et al. 2025)²¹) compared optimization methods for choosing the best system size in remote areas. (Bobyl et al. 2025)²²) worked on off-grid hybrid power plants for rural electrification. (Agajie et al. 2024)^{23,27}) improved Ethiopia's power supply reliability by optimizing hybrid energy systems. (Zhou et al. 2025)²⁴) gave insights into commercial uses of hybrid systems in small hotels. (Guvén et al. 2025)^{25,26}) also applied HRES for electric vehicle charging systems. (Hasan et al. 2024)^{28,29}) targeted industrial energy shortages in South Asia with renewable microgrids. (Molu et al. 2024)³⁰) did a cost and performance study of hybrid energy systems in Cameroon.

Recent studies have focused on improving hybrid renewable energy systems (HRES) for better cost, performance, and environmental impact. (Garip et al. 2022)⁴³) carried out a techno-economic study of grid-connected HRES to reduce both cost and emissions. (He et al. 2023)⁴⁴) used an advanced algorithm to design a fuel cell-solar-wind system with better efficiency. (Escoto and Abundo 2025)⁴⁵) tested the use of HRES for electric boat charging and found it sustainable and practical. (Zhang et al. 2024)⁴⁶) applied a new optimization method for better system sizing and cost analysis. (Amer et al. 2013)⁴⁷) used PSO to reduce overall HRES cost successfully.

Despite many studies, only a few focus on Indian educational buildings using grid-connected hybrid systems that combine solar, wind, batteries, and diesel with power quality analysis. Most past works looked at cost savings or remote area electrification, but not at both economic and technical aspects like voltage control, frequency regulation, and harmonic distortion in real buildings. This creates a clear research gap. The present study fills this gap by designing and testing an optimized hybrid system for an educational building in Jaipur using HOMER and Python. It aims to reduce energy cost, improve reliability, and ensure clean and stable electricity for future-ready educational infrastructure. Previous studies have HRES simulation for various options but very less research publications have optimal solutions of the HRES using ML methods. In present study the hybrid ML methods have selected to optimal the HRES system with optimal SPV power plant and BESS system.

Table 1 Contribution of various publications on HRES system

Publications	Different Systems of HRES				Micro Grid System		Power Quality System		
	SPV	Wind	Con Gen	BESS	ON	OFF	BESS	Voltage	f
31)	Y	Y	N	Y	N	Y	Y	Y	Y
32)	Y	Y	N	Y	N	Y	Y	Y	Y
33)	Y	Y	Y	Y	N	Y	Y	Y	Y
34)	Y	Y	Y	Y	N	Y	N	N	N
35)	Y	Y	N	N	N	Y	N	N	N
36)	Y	Y	N	Y	N	Y	Y	Y	Y
37)	Y	Y	Y	Y	N	Y	N	N	N
Current	Y	Y	Y	Y	Y	N	Y	Y	Y

4. Material and Method

The simulation technique used in this study was based on the understanding that renewable energy systems were greatly influenced by geographical and environmental factors, requiring accurate simulation data collection. The first step was identifying relevant renewable energy sources and then utilizes the HOMER⁴⁸) program to assess economic factors and get key indicators, as shown in Figure 1. In addition, simulation data for weather of the Jaipur for solar power facilities is generated using SAM software³⁸). The procedure begins by collecting meteorological, energy, and economic data of the case study location and in present study the Jaipur rural area was selected for the investigation. The data is subsequently analyzed using HOMER software to enhance the architecture of the Hybrid Renewable Energy System (HRES), guaranteeing complete dependence on renewable resources and meeting the entire electricity requirement. The proposed renewable energy solution is guaranteed to be reliable, efficient, and economically viable through the use of a systematic approach, as shown in the accompanying flowchart. As seen in the flow diagram, the proper design of system components was crucial in present study. The all components of the HRES system were generated in HOMER software and then best possible HRES were solved using the HOMER. All solved cases then simulated using google collab ML code to find the best optimal solution of the HRES in rural area based educational building. In present study the wind turbine was proposed on the educational building and have less electrical energy generation as a prototype. The grid was connected with the educational building already. The main outcome parameter was LCOE (levelized cost of the electricity). Solor photovoltaic power plant was proposed on the roof of the educational building. The details of the study was discussed in the next section of the research study.

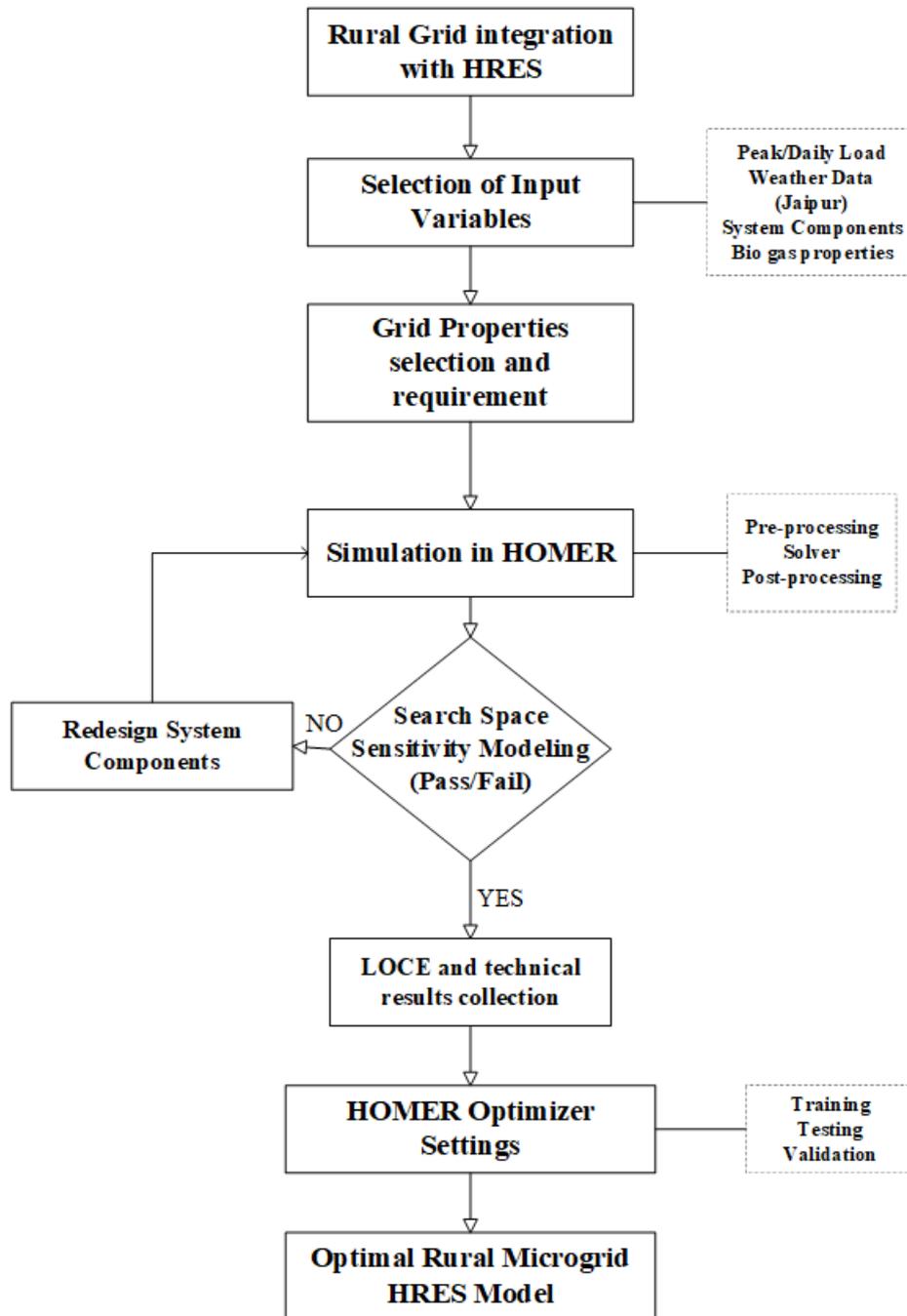


Fig. 1 Research flow diagram adopted in present investigation

4.1 HOMER Software

In present study, HOMER software was used because it is a reliable and widely used tool for designing and analyzing hybrid energy systems. HOMER, developed by the U.S. National Renewable Energy Laboratory (NREL), helps users model systems that include solar panels, wind turbines, batteries, generators, and grid connections. It is popular in academic research due to its accuracy and ease of use, with over 250,000 users worldwide as of 2022⁴⁹. The software works by first simulating how the energy system performs over time, then calculating the energy balance, total cost, and environmental impact. It provides a list of the most cost-effective system options and can perform sensitivity analysis to show how different factors (like fuel cost or sunlight levels) affect the results. HOMER^{50,51} saves time and effort compared to manual calculations and is especially useful when testing many system combinations to find the best and most affordable solution. HOMER have internal optimization tool also which help to find the initial optimized cases of the HRES system.

4.2 Region Selection

In present study the educational building was selected to simulate the HRES system which having SPV, wind, grid and BESS system to make the low cost LOCE for the HRES system. The google map image of the selected region was show in figure 2 in location of the Jaipur, India.



Fig. 2 Selection of region for HRES design and optimization

The educational building has cluster of the buildings like main block, lecture blocks, hostels and administrative blocks. The region latitude and longitude were (26.84, 75.56) used for the weather data collection. The reason to select this region for the simulation-based study because here lots of the land availability for the SPV plants installation and wind speed was suitable for small wind turbines.

4.3 HRES System Modeling

4.3.1 Electrical Load

In present study educational building was selected for the development of the HRES system. In this building various other buildings were present like administrative building, lecture building, hostel building, and main building block. The electrical load was the collective sum of the all buildings and the present in the figure 3. The average electrical load (kWh/day) of the building cluster was 3745 kWh/day and the peak electrical load was 446.43 kW and the load factor of the study was 0.35. In HOMER software the random variability was set to 10% for each option (Day to Day and Timestep). The random variability helps to make the realist electrical load conditions for the whole year in the HOMER software. The monthly load for the whole year was show in figure 3. The educational building has the self-grid system which help to make the electrical load calculation easy. In this study total AC, total fans, total lights, total other electrical equipment were used and calculated the rated power of the all instruments. The load profile shows the peak load among 10 am to 5 pm due to educational activities in the building cluster.

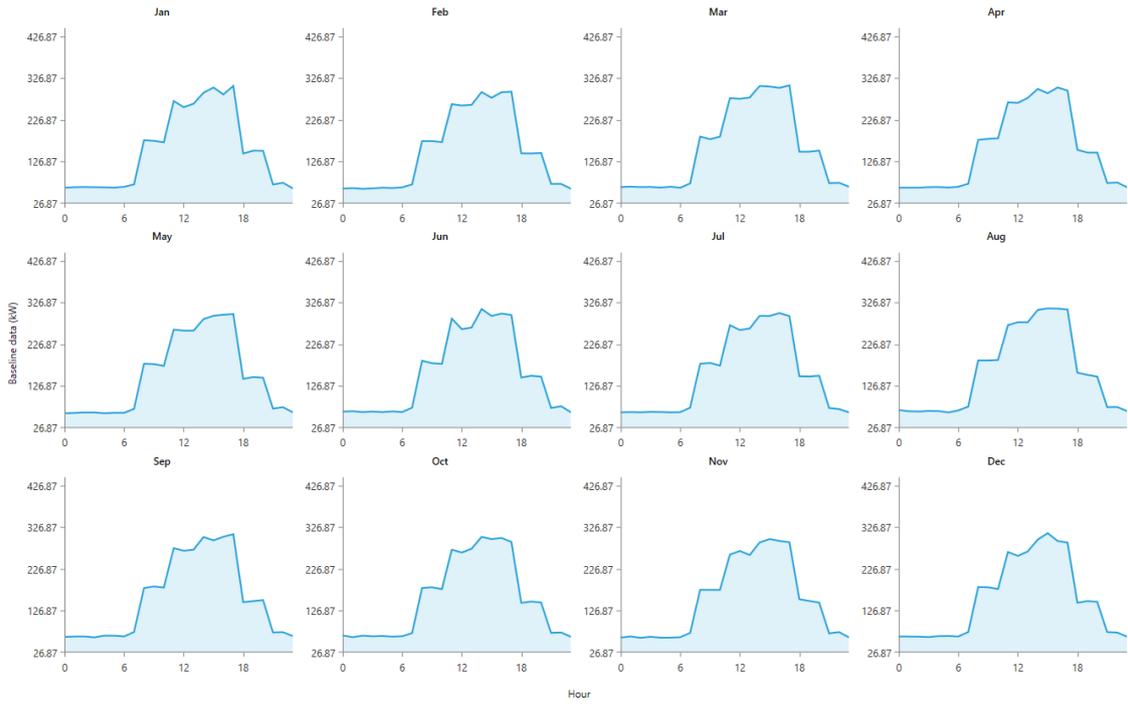


Fig. 3 profile plot of the electrical load of the educational building cluster selected in present investigation

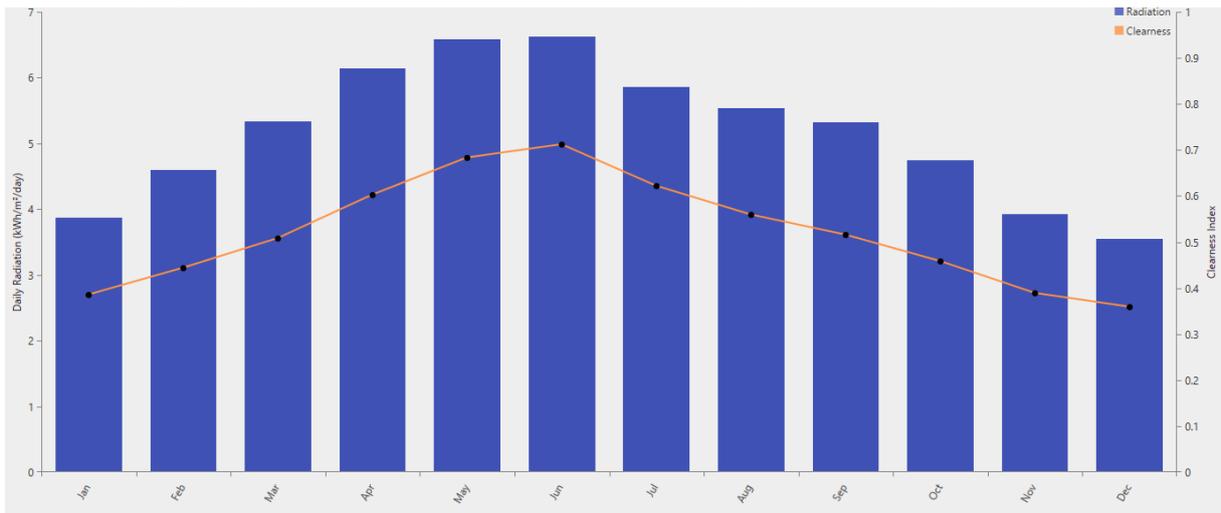


Fig. 4 Global horizontal irradiance [GHI] of Jaipur



Fig. 5 Average wind speed of Jaipur

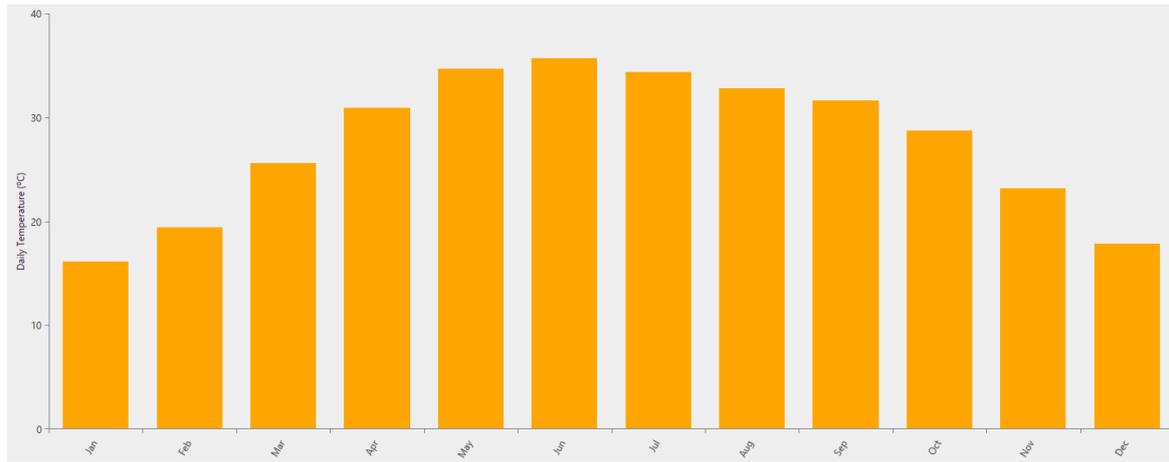


Fig. 6 Daily Temperature of Jaipur

4.3.2 Resources

HRES simulation was dependent on the weather resources like solar resources (global horizontal irradiance (GHI), wind, air temperature of the location where HRES was proposed. The GHI, wind and air temperature plots were present in figure 4, figure 5 and figure 6 respectively. The resources dataset was collected with the help of SAM software which help to give the weather data of the Jaipur (India). The other important parameters of the region and resources were present in table 2.

Table 2 weather and resources data of the proposed location of HRES

Parameters	Value
Latitude	26.84
Longitude	75.56
Diesel Price (INR/L)	90~92
Grid Electricity Price (INR/kWh)	8.5

4.3.3 System Components

In present study HRES system which was developed for the simulation was show in figure 7 in which schematic of the proposed HRES system with all required components.

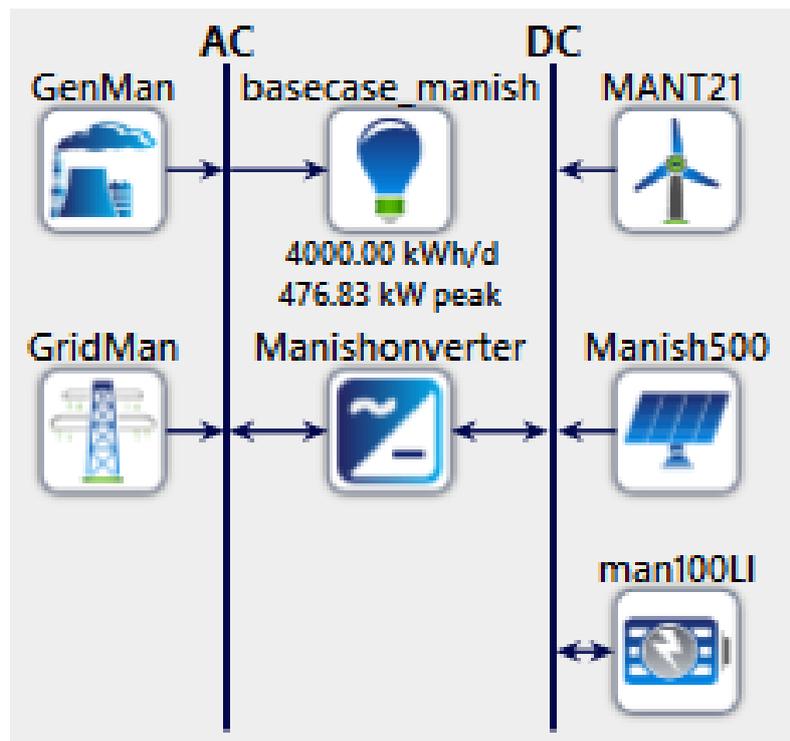


Fig. 7 Schematic of the proposed HRES with system components

In order to fulfil the high electricity demand of the educational building installed electrical sub division station, which reaches a peak of 475 kW and requires a daily energy output of 4000 kWh, the system incorporates a range of generating and conversion units. The system consists of the 500 kW SPV power plant, one wind turbine of 100 kW and one BESS system to store the electricity. As seen in the schematic diagram, the DC to AC conversion was done using convertor installed in the proposed HRES system. For more better analysis the AC bus was connected with conventional diesel-based generator and conventional grid.

Present schematic diagram presents a detailed plan for the proposed Hybrid Renewable Energy System (HRES), showcasing the movement of energy from its production to its utilization. The detailed configurations of the system were present in table 3.

Table 3 configuration of system components used in proposed HRES system

Component	Capacity (kW)	Price (/100 kW)	Reference
SPV-I	500	3.5 M	[39]
Con-Gen-I	100	1.2 M	[40]
BESS-1	100	1.2 M	
Wind-I	100	10M	[50]
DC-AC Convertor	1000	0.5 M	[50]

As seen in table 3, the cost parameters was considered and technical parameters were considered as per literature review. The all possible HRES combinations made for present investigation present in figure 8. As seen in the figure 8 the total five cases were selected for the optimum solution of the HRES system selected for the present study. The HOMER software was used for the simulation of the HRES system.

4.3.4 HRES System Scenarios

In present study several scenarios were generated to test the HRES system for optimal solutions. The first scenarios were Only Grid connected electricity, second scenario was grid connected with SPV power plant, third scenarios were grid SPV and wind power plant and last scenario was SPV, wind and BESS with grid connected. All details were present in table 4 as per study requirement.

Table 4 HRES system scenarios generated for present study

Scenario	SPV	Wind	BESS	Generator	Grid
I	No	No	No	No	Yes
II	Yes	No	No	No	Yes
III	Yes	Yes	No	No	Yes
IV	Yes	Yes	Yes	Yes	Yes

The proposed HRES system scenarios selected for the present study was seen in figure 9, in which red arrow show the real scenarios solved in HOMER software.

5 Result and Discussion

The present study's analysis produced valuable findings concerning the energy procurement needs and the performance of the Hybrid Renewable Energy System (HRES) based on the Renewable Fraction. The monthly baseline power purchase requirement was determined, reflecting fluctuating levels of demand over the course of the year. The annual electricity purchases from grid were equal to 1,825,000 kWh/yr, inclusive of peak load costs and demand charges. In present section total four cases were investigated as like table 4.

5.1 Electrical Production Comparison

In present section the electrical energy production in four scenarios were discussed and present in table 5. As seen table 4, the production of electrical production was changed as per component addition.

The results in Table 5 show how much electricity was produced from the grid and from renewable sources in four different scenarios. In Scenario I, all the electricity (1,825,000 kWh/year) came from the grid, with no renewable energy used. In Scenario II, the system used a mix of grid and renewable energy, with 52.9% of the power coming from renewables. Scenarios III and IV had the highest renewable energy use, both producing 1,825,000 kWh/year from renewables, which made up over 75% of the total electricity. This shows that the system can reduce grid use by increasing renewable energy share.

The electrical production in best case IV which have all renewable components and BESS was show in figure 10. This plot clearly indicates the all sections of electrical production in HRES system.

Table 5 HRES system electrical production comparison

Scenarios	Production-Grid (kWh/Yr)	Production-Renew (kWh/Yr)	Renewable Fraction (%)
I	1825000	0	0
II	983384	1163259	52.9
III	578621	1825000	75.1
IV	577165	1825000	75.2

The grid purchase for all scenarios were also present in table 6 which help to find the dependency of the grid purchase from the system and help to make the role of the HRES system.

Table 6 Electrical Energy Purchase from grid for all scenarios

Month	I	II	III	IV
1	153,233	95,741	59,693	59,583
2	135,616	75,398	48,760	48,639
3	160,066	84,843	56,776	56,616
4	150,529	72,513	42,276	42,164
5	151,928	70,018	26,237	26,165
6	151,891	69,190	24,195	24,113
7	153,115	73,578	27,765	27,667
8	160,570	83,211	42,260	42,135
9	152,210	82,753	42,669	42,557
10	153,640	85,106	65,919	65,731
11	147,462	92,095	70,908	70,772
12	154,739	98,939	71,161	71,024

Table 6 shows the monthly amount of electricity purchased from the grid under four different system scenarios. In Scenario I, there is no use of renewable energy, so all the required electricity is bought from the grid. As a result, grid consumption is the highest every month, ranging from around 135,000 to 160,000 kWh.

This means the system is fully dependent on the grid throughout the year. In Scenario II, a partial hybrid system is used where renewable energy is added to reduce grid use. The grid power requirement drops significantly in all months. For example, in January, it reduces from 153,233 kWh (in Scenario I) to 95,741 kWh. The same trend continues in all other months, showing noticeable energy savings due to the use of solar, wind, and battery storage.

Scenario III and Scenario IV show the lowest grid electricity usage across all months. In these two scenarios, the system is designed with maximum use of renewable sources and energy storage. In June, grid power drops from 151,891 kWh (Scenario I) to only 24,195 kWh (Scenario III) and 24,113 kWh (Scenario IV). The monthly values in Scenario III and IV are almost the same, proving that both configurations are efficient and reliable in reducing grid dependence. As renewable energy use increases from Scenario I to IV, the amount of electricity purchased from the grid drops significantly. This shows that a well-designed hybrid system can save energy, reduce costs, and lower dependency on external power sources.

5.2 Economical Comparison

In present study the economic comparison was performed for all scenarios and the results were present in and figure 11. The results from the HOMER software show how different hybrid energy system combinations affect the total cost, component-wise spending, and savings. The first case (Base Case) shows a grid-only system, where almost all of the cost (₹234.48 million) goes to operation and maintenance (O&M). There is a small capital cost of ₹1.5 million, but this system is highly dependent on grid electricity.

Quantity	Value	Units	Quantity	Value	Units	Quantity	Value	Units
Batteries	1.00	qty.	Autonomy	0.384	hr	Average Energy Cost	9.81	₹/kWh
String Size	1.00	batteries	Storage Wear Cost	0.246	₹/kWh	Energy In	84.3	kWh/yr
Strings in Parallel	1.00	strings	Nominal Capacity	100	kWh	Energy Out	75.9	kWh/yr
Bus Voltage	600	V	Usable Nominal Capacity	80.0	kWh	Storage Depletion	0	kWh/yr
			Lifetime Throughput	1,200	kWh	Losses	8.43	kWh/yr
			Expected Life	15.0	yr	Annual Throughput	80.0	kWh/yr

Fig. 8 BESS input conditions used in present study

					Manish500 (kW)	Manish500-MPPT (kW)	MANT21	Gen_Man (kW)	man100LI
					537	500	4		
					531	500	4		1
					537	500	4	750	
					541	500	4	750	1
							6		
							6		1
							6	750	
							6	750	1
					751	500			
					748	500			1
					751	500		750	
					748	500		750	1
									1
								750	
								750	1

Fig. 9 proposed possible combinations of HRES system for present investigation



System Architecture: Autosize Genset (750 kW) ManishGrid (4,500 kW)
 SolarMax 500RX A manish (541 kW/500 kW) mansih100kWh Li-Ion (1.00 strings) AMB Cycle Charging
 Manish M-21-ETR [100kW] (4.00) Manish Converter (515 kW)

Total NPC:	₹175,507,200.00
Levelized COE:	₹5.83
Operating Cost:	₹6,363,482.00

SolarMax 500RX A manish Manish M-21-ETR [100kW] ManishGrid Manish Converter Emissions
 Cost Summary Cash Flow Compare Economics Electrical Fuel Summary Autosize Genset Renewable Penetration mansih100kWh Li-Ion

Production	kWh/yr	%
SolarMax 500RX A manish	878,424	34.7
Autosize Genset	0	0
Manish M-21-ETR [100kW]	1,072,495	42.4
Grid Purchases	577,165	22.8
Total	2,528,084	100

Consumption	kWh/yr	%
AC Primary Load	1,825,000	78.4
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	504,239	21.6
Total	2,329,239	100

Quantity	kWh/yr	%
Excess Electricity	106,923	4.23
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	75.2	%
Max. Renew. Penetration	175	%

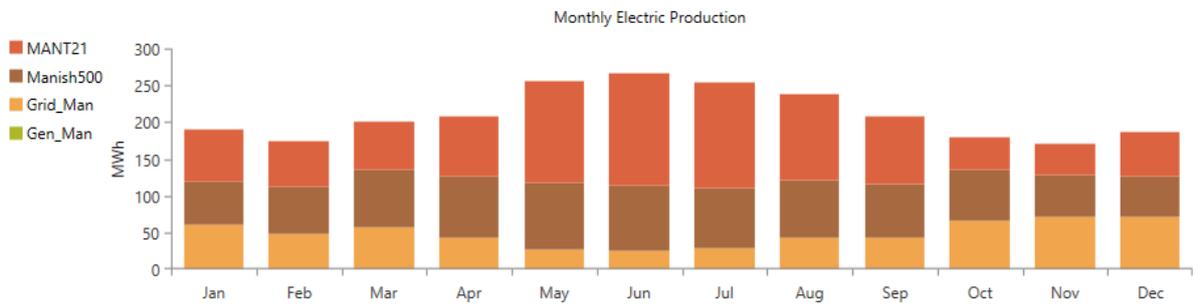
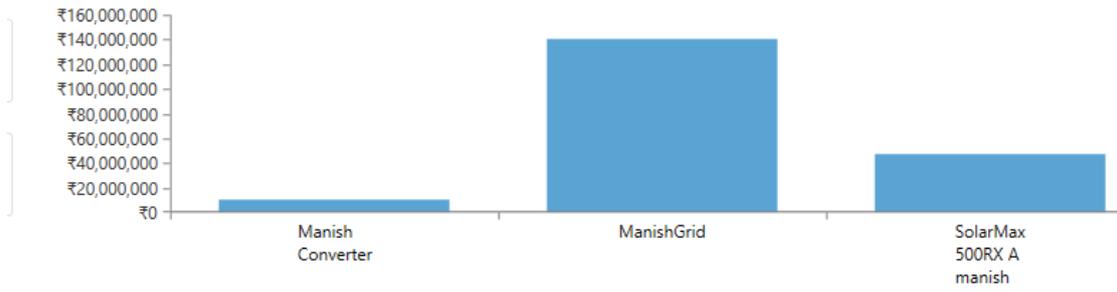


Fig. 10 Annual electrical requirement of HRES system (SPV+Wind+BESS+Grid)



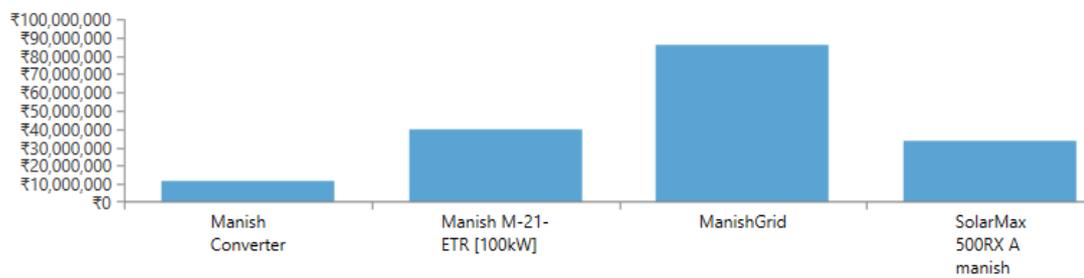
Component	Capital (₹)	Replacement (₹)	O&M (₹)	Fuel (₹)	Salvage (₹)	Total (₹)
ManishGrid	₹1,500,000.00	₹0.00	₹232,987,793.48	₹0.00	₹0.00	₹234,487,793.48
System	₹1,500,000.00	₹0.00	₹232,987,793.48	₹0.00	₹0.00	₹234,487,793.48

Grid cost summary



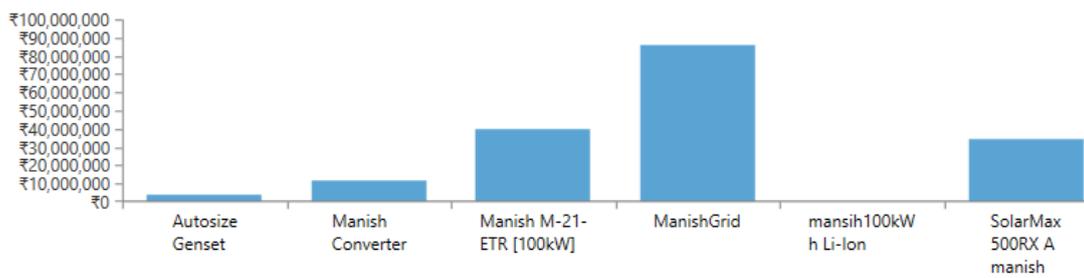
Component	Capital (₹)	Replacement (₹)	O&M (₹)	Fuel (₹)	Salvage (₹)	Total (₹)
Manish Converter	₹9,969,481.36	₹1,004,152.70	₹0.00	₹0.00	-₹188,991.67	₹10,784,642.38
ManishGrid	₹11,500,000.00	₹0.00	₹128,799,907.22	₹0.00	₹0.00	₹140,299,907.22
SolarMax 500RX A manish	₹37,567,655.11	₹0.00	₹9,713,129.66	₹0.00	₹0.00	₹47,280,784.77
System	₹59,037,136.47	₹1,004,152.70	₹138,513,036.89	₹0.00	-₹188,991.67	₹198,365,334.38

Grid+SPV cost summary



Component	Capital (₹)	Replacement (₹)	O&M (₹)	Fuel (₹)	Salvage (₹)	Total (₹)
Manish Converter	₹10,766,019.03	₹1,083,801.55	₹0.00	₹0.00	-₹203,982.39	₹11,645,838.19
Manish M-21-ETR [100kW]	₹40,000,000.00	₹0.00	₹0.00	₹0.00	₹0.00	₹40,000,000.00
ManishGrid	₹11,500,000.00	₹0.00	₹74,785,203.67	₹0.00	₹0.00	₹86,285,203.67
SolarMax 500RX A manish	₹26,860,068.00	₹0.00	₹6,944,679.47	₹0.00	₹0.00	₹33,804,747.47
System	₹89,126,087.03	₹1,083,801.55	₹81,729,883.14	₹0.00	-₹203,982.39	₹171,735,789.33

Grid+SPV+Wind cost summary



Component	Capital (₹)	Replacement (₹)	O&M (₹)	Fuel (₹)	Salvage (₹)	Total (₹)
Autosize Genset	₹3,750,000.00	₹0.00	₹0.00	₹0.00	-₹87,588.34	₹3,662,411.66
Manish Converter	₹10,870,227.88	₹1,094,221.79	₹0.00	₹0.00	-₹205,943.58	₹11,758,506.09
Manish M-21-ETR [100kW]	₹40,000,000.00	₹0.00	₹0.00	₹0.00	₹0.00	₹40,000,000.00
ManishGrid	₹11,500,000.00	₹0.00	₹74,431,723.77	₹0.00	₹0.00	₹85,931,723.77
mansih100kWh Li-Ion	₹70,000.00	₹29,699.17	₹12,927.52	₹0.00	-₹5,589.68	₹107,037.00
SolarMax 500RX A manish	₹27,053,001.75	₹0.00	₹6,994,562.56	₹0.00	₹0.00	₹34,047,564.31
System	₹93,243,229.63	₹1,123,920.96	₹81,439,213.84	₹0.00	-₹299,121.61	₹175,507,242.83

Fig. 11 Cost summary of the final HRES system

In the second case, a hybrid system is introduced with solar panels, converter, and grid connection. The total cost reduces to ₹198.36 million. Most of the cost is due to grid O&M (₹128.79 million), followed by solar panel investment

(₹37.56 million) and converter (₹9.96 million). This shows that using solar energy reduces grid dependence, and even with a higher initial investment, long-term costs are lower.

The third case adds more solar capacity and uses a more powerful converter. The total cost further drops to ₹171.73 million, and the O&M cost is much lower (₹81.72 million). Although the capital investment is higher (₹89.13 million), it includes ₹40 million for a high-efficiency solar inverter. The lower O&M and grid usage suggest that this setup is more cost-efficient over the long term, making it a better choice for energy sustainability. In the fourth and most advanced system, a diesel generator, lithium-ion battery, solar system, and grid connection are all included. This hybrid system shows the lowest grid O&M cost (₹74.43 million) and smart energy storage with a 100kWh battery. The total cost is ₹175.51 million, which is slightly higher than the third case due to battery and generator costs. However, this system provides better energy backup and storage, which is helpful for maintaining continuous power during outages and load fluctuations.

Across all scenarios, it is clear that hybrid systems combining solar, batteries, and grid offer the best results in terms of cost-saving, energy reliability, and future expansion possibilities. The results prove that shifting from a grid-only system to a hybrid model not only reduces long-term operational costs but also enhances energy security and performance, which is very important for institutions like schools or colleges. Thus, based on cost and reliability, the third scenario offers the most balanced and affordable system, while the fourth system is best for power quality and storage needs despite a slightly higher cost.

5.3 LCOE Comparison

Table 7 shows the comparison of four different energy system scenarios based on three important values: Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Operation & Maintenance (O&M) Cost. In Scenario I, the system uses only grid power. This results in the highest NPC of ₹234.48 million and the highest LCOE of ₹9.94/kWh. The O&M cost is also very high, at ₹18.02 million per year. This means that relying fully on grid electricity becomes very expensive in the long run. Scenario II introduces a hybrid system that uses solar energy along with the grid. As a result, the total NPC drops to ₹198.36 million and the LCOE decreases to ₹7.35/kWh. The O&M cost also reduces to ₹10.77 million. This clearly shows that using some renewable energy helps reduce electricity costs and improves system performance.

Table 7 LCOE comparison for all four scenarios

Scenarios	NPC	LCOE	O and M cost
I	234,487,800	9.94	18,022,630
II	198,365,300	7.35	10,777,650
III	171,735,800	5.72	6,390,222
IV	175,507,200	5.83	6,363,482

In Scenario III, more renewable sources like wind, solar, and battery storage are added. This scenario shows the lowest NPC of ₹171.73 million and the lowest LCOE of ₹5.72/kWh. The O&M cost is also the lowest, at ₹6.39 million. These results show that using more renewable energy and less grid power can make the system highly cost-effective and sustainable over time. Scenario IV is similar to Scenario III but includes an additional battery and generator setup for better reliability. The NPC is slightly higher than Scenario III at ₹175.50 million, and the LCOE is ₹5.83/kWh. The O&M cost is ₹6.36 million, which is still much lower than in the grid-only case. The results clearly show that hybrid systems using renewable energy are much better in terms of cost and efficiency compared to systems that rely only on the grid. Scenario III stands out as the most economical and efficient choice, while Scenario IV offers better power backup and reliability at a slightly higher cost. This proves that investing in renewable energy systems for institutions like schools and colleges is a smart way to reduce electricity bills and ensure reliable and clean energy.

6. Conclusion

This study shows that Hybrid Renewable Energy Systems (HRES) are a smart and useful way to provide electricity to places like rural villages and educational buildings. By using clean energy sources like solar and wind along with the regular electricity grid, we can create a system that is both reliable and good for the environment. The results from this study clearly show that increasing the use of renewable energy reduces the need to buy electricity from the grid and also lowers overall costs. In this research, four different system setups (scenarios) were compared. The first system (Scenario I), which used only grid electricity, had the highest cost with a Net Present Cost (NPC) of ₹234.48 million, Levelized Cost of Energy (LCOE) of ₹9.94/kWh, and Operation & Maintenance (O&M) cost of ₹18.02 million. When renewable sources were added in Scenario II, the costs dropped to ₹198.36 million NPC, ₹7.35/kWh LCOE, and ₹10.77 million O&M. In Scenario III, where renewable energy was used the most, the NPC dropped to ₹171.73 million, LCOE to ₹5.72/kWh, and O&M to ₹6.39 million — the lowest among all. Scenario IV also performed well with ₹175.50 million NPC, ₹5.83/kWh LCOE, and ₹6.36 million O&M. These results prove that HRES not only helps reduce electricity costs but also provides clean and stable power. This is very helpful for rural and remote areas where regular grid supply may be weak or unavailable. Using HRES can also help improve education, health, and jobs by giving people better access to

electricity. In the future, more research and practical use of HRES will be important to reduce energy poverty and support sustainable development in India and across the world.

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