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Integrating Solar and Wind Energy: A Technical and Economic Perspective

Jinendra Rahul*, [1], and Ramesh Kumar Pachar*

Abstract – *This paper presents a comprehensive economic and technical analysis of a hybrid solar and wind energy microgrid system. Utilizing HOMER software for simulation, it evaluates the feasibility of integrating solar photovoltaic (PV) panels and wind turbines in a microgrid to meet energy demands efficiently and cost-effectively. The study considers key parameters such as capacity shortage, energy costs, and system components, including PV, wind turbines, storage systems, converters, and the grid. The economic analysis reveals the Total Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), offering insights into the financial viability of the hybrid system compared to traditional energy sources. The technical analysis focuses on energy production, consumption, and system efficiency, highlighting the performance of individual components and the overall reliability of the microgrid. The findings demonstrate the potential for significant cost savings and enhanced energy security through the adoption of hybrid renewable energy systems. The study concludes with recommendations for policymakers and stakeholders, emphasizing the benefits of renewable energy integration and the importance of supportive policies to facilitate the transition to sustainable energy solutions.*

Keywords – Economic and Technical Analysis, Hybrid Microgrid, Renewable Energy Integration, Solar Photovoltaic (PV), Wind Turbines.

1. INTRODUCTION

Renewable energy integration into the global grid is vital for sustainability and combating climate change. Unlike fossil fuels, renewable sources like hydro, wind, solar etc. are abundant and generate minimal greenhouse gases, making them crucial for reducing carbon footprints and mitigating global warming [1]. Fossil fuel energy production is the leading cause of global CO_2 emissions, so transitioning to renewables is key to meeting international climate goals, including the Paris Agreement [2]. Additionally, renewable energy diversification strengthens energy security by reducing reliance on imported fuels. This shift not only aligns with environmental objectives but also strengthens the energy supply's resilience, making it a vital element of the global strategy to tackle climate challenges [3].

Beyond environmental advantages, the integration of renewable energy drives economic growth and job creation. The renewable energy industry has become one of the fastest-growing sectors globally, generating millions of jobs and encouraging innovation in energy technologies [4]. This shift also fosters local economic development by enabling decentralized energy production, particularly in remote and underserved areas [5].

Advancing grid infrastructure and energy storage is vital for integrating renewable energy effectively. Smart grids, paired with advanced storage systems, enhance management of renewable energy's intermittent nature, ensuring stable and reliable supply [6]. Supportive policies and regulatory frameworks also play a main role by offering incentives and establishing targets for renewable energy adoption [7].

2. LITERATURE REVIEW

Renewable Energy Microgrids (REMs) are localized networks integrating renewable sources like solar, wind, and biomass to enhance energy reliability and reduce reliance on fossil fuels. They are a sustainable solution for decentralized energy production, with research emphasizing their design, optimization, and performance.

Early research on REMs emphasized the technical and economic feasibility of integrating multiple renewable sources. For instance, work by Ahmed et al. [8] demonstrated that combining solar and wind power in microgrids could significantly improve system reliability and efficiency. Similarly, studies by Zhang et al. [9] examined the benefits of incorporating energy storage systems to mitigate the intermittency of renewable sources, enhancing overall grid stability and performance.

Optimization techniques have also been a significant focus in REM research. Liu et al. [10] explored various optimization models for sizing and dispatching renewable energy resources in microgrids, highlighting the role of advanced algorithms in improving cost-effectiveness and operational efficiency. These studies underscore the importance of sophisticated control strategies to balance supply and demand dynamically.

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Additionally, recent research has examined the integration of smart grid technologies and advanced forecasting methods in REMs. Yang et al. [11] investigated how smart grid technologies, such as demand response and real-time monitoring, can enhance the management and efficiency of renewable energy microgrids. The incorporation of AI and machine learning for predictive maintenance and performance optimization has also been explored, as noted by Chen et al. [12].

The integration of wind and solar energy offers substantial economic and technical benefits, making it a promising approach to achieving sustainable and reliable energy systems. Combining these two renewable sources leverages their complementary nature, addressing intermittency issues and optimizing energy output.

From a technical perspective, solar and wind energy systems complement each other well. Solar power generation peaks during daylight hours, while wind energy can be more productive during periods of low sunlight or at night. This complementary generation profile enhances the reliability and consistency of renewable energy supply. For instance, during the day, solar energy can meet the energy demand, and when the sun sets, wind energy can take over, reducing the reliance on fossil fuels [13]. Moreover, the use of advanced forecasting and control technologies can further optimize the integration of these resources, improving grid stability and reducing curtailment losses [14].

Economically, integrating solar and wind energy systems can lead to significant cost savings and increased economic efficiency. The combined deployment of these technologies can lower overall system costs through economies of scale and reduced need for backup power. Studies show that hybrid systems can enhance the financial viability of renewable projects by spreading investment risks and capitalizing on diverse revenue streams [15]. Additionally, the reduced need for conventional energy sources can lower fuel and maintenance costs, further driving economic benefits [16].

Hybrid Renewable Energy Systems (HRES) integrate diverse energy sources like solar, wind, and biomass to provide reliable and sustainable power. These systems promote job creation and stimulate local economies through installation, operation, and maintenance activities [17]. However, HRES face significant challenges, including the complexity of integrating multiple sources with varying outputs and reliability, the intermittency of renewables like solar and wind, and the need for advanced energy storage and smart grid technologies to balance supply and demand. High initial deployment costs further hinder adoption. Despite these obstacles, HRES remain a promising solution for maximizing renewable energy utilization and supporting local economic development [18].

While the long-term benefits of renewable energy are clear, the upfront investment required for infrastructure, technology, and grid integration can be prohibitive, particularly in developing regions [19]. Additionally, the variability in renewable energy production requires sophisticated control systems and predictive models to optimize performance and reduce wastage, adding further complexity and cost [20].

On the advancement front, there have been significant improvements in energy storage technologies, such as lithium-ion batteries and supercapacitors, which enhance the feasibility of HRES by providing reliable backup power and improving grid stability [21]. Moreover, the integration of artificial intelligence (AI) and machine learning (ML) in HRES has enabled more accurate forecasting, demand prediction, and real-time system optimization, thus enhancing overall efficiency [22].

The main contribution of paper as follows:

1. The paper presents a detailed economic analysis, showing that hybrid solar and wind microgrid systems can substantially lower energy costs by achieving reduced Total Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) compared to conventional energy sources.
2. It offers an in-depth technical analysis, highlighting the efficiency and reliability of hybrid microgrid systems. The study examines energy production, consumption patterns, and system component performance, providing valuable insights for optimizing hybrid energy systems.
3. The research emphasizes the successful integration of solar PV system and wind turbines, showcasing the potential of hybrid systems to enhance energy security and sustainability. The findings illustrate how combined renewable energy sources can meet energy demands more effectively than standalone systems.
4. The paper concludes with practical recommendations for policymakers and stakeholders, advocating for supportive policies and investments to facilitate the adoption of HRES. These guidelines aim to promote the transition to sustainable energy solutions, addressing both environmental and economic challenges

3. METHODOLOGY

HOMER (Hybrid Optimization Model for Multiple Energy Resources) is a widely used simulation tool designed to model and optimize HRES. Developed by the NREL (National Renewable Energy Laboratory), HOMER allows users to simulate various configurations of hybrid systems, assess their economic and technical feasibility, and identify optimal designs. It incorporates detailed modeling of renewable energy sources, storage systems, and load profiles, providing users with a comprehensive analysis of system performance under different scenarios [23], [24].

3.1 System Architecture

The microgrid system is designed for the specific location at RVVR+H76 Sector 8 Public Park 1, Sector 8, Ghati Karolan, Jaipur, Rajasthan 302017, India, with latitude 26°50.6′ N and longitude 75°53.4′ E. The software uses input data such as wind speed, solar irradiation (with clearness index), and temperature, which are sourced from NASA's (National Aeronautics and Space Administration) Prediction of Worldwide Energy Resources. This data enables accurate modeling and analysis of energy resources based on real-world environmental conditions. The corresponding figures (Fig. 1 and Fig. 2) and Table 1 display load profile of proposed system. The design of the microgrid accounts for the residential load, represented by a load curve that was plotted and considered in the sizing process. Key metrics include an annual average solar GHI of 5.47 kWh/m^2/day, annual wind speed averaging 4.76 m/s and an average temperature of 25.90°C.

Table 1. Hourly average load demand for typical lower-, middle- and upper-class households in selected area.

Duration	Average daily load (kW)	Duration	Average daily load (kW)
00:00-01:00	623.0441	12:00-13:00	324.9702
01:00-02:00	628.776	13:00-14:00	419.5602
02:00-03:00	625.6115	14:00-15:00	420.6486
03:00-04:00	627.3186	15:00-16:00	384.7142
04:00-05:00	616.3969	16:00-17:00	373.4436
05:00-06:00	135.5824	17:00-18:00	112.991
06:00-07:00	379.295	18:00-19:00	130.0524
07:00-08:00	1706.005	19:00-20:00	1383.966
08:00-09:00	537.3896	20:00-21:00	1013.745
09:00-10:00	189.423	21:00-22:00	1594.805
10:00-11:00	111.1551	22:00-23:00	1243.731
11:00-12:00	178.1305	23:00-24:00	786.3739

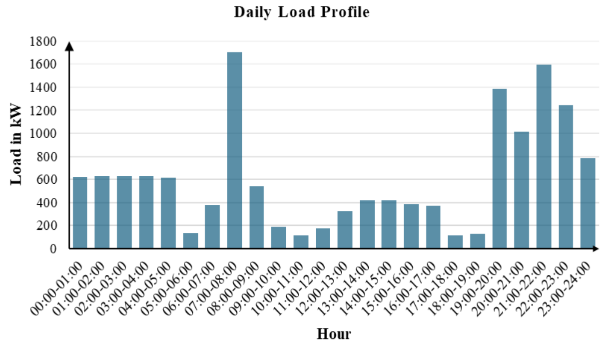


Fig. 1. Average daily load profile for lower-, middle- and upper-class households in selected area.

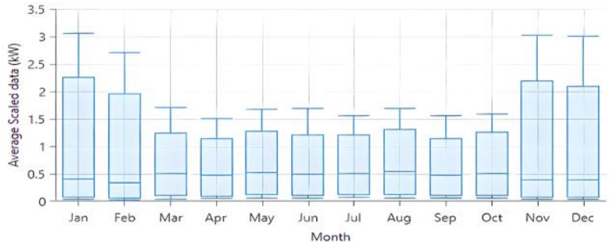


Fig. 2. Seasonal load profile of households in selected area.

The Monthly average daily radiation with clear index and wind speed data in selected area data for this study is sourced from the NASA POWER database. Table 2 and Fig. 3 present the monthly solar radiation profile alongside the clearness index. Table 3 and Fig. 4 show the monthly average daily wind speed for the selected area.

Table 2. Monthly average daily radiation with clear index in selected area (NASA).

Month	Daily Radiation (kWh/m2/day)	Clearness Index	Month	Daily Radiation (kWh/m2/day)	Clearness Index
Jan	4	0.622	Jul	5.1	0.457
Feb	4.71	0.618	Aug	4.71	0.447
Mar	5.46	0.599	Sep	5.12	0.543
Apr	6.11	0.589	Oct	4.79	0.602
May	6.38	0.575	Nov	4.16	0.627
Jun	6.24	0.552	Dec	3.74	0.619

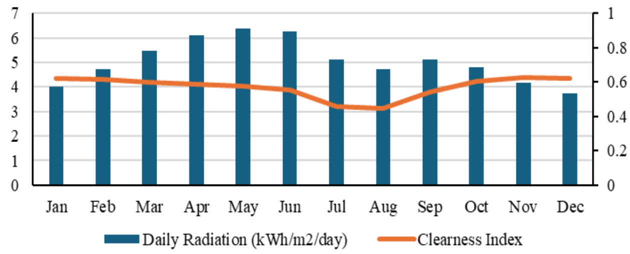


Fig. 3. Global solar radiation of selected area, clearness index. Data from (NASA).

Table 3. Monthly average daily wind speed selected area (NASA).

Month	Average wind speed (m/s)	Month	Average wind speed (m/s)
Jan	4.330	Jul	5.250
Feb	4.630	Aug	4.730
Mar	4.970	Sep	4.580
Apr	5.310	Oct	3.670
May	6.300	Nov	3.590
Jun	5.940	Dec	3.850

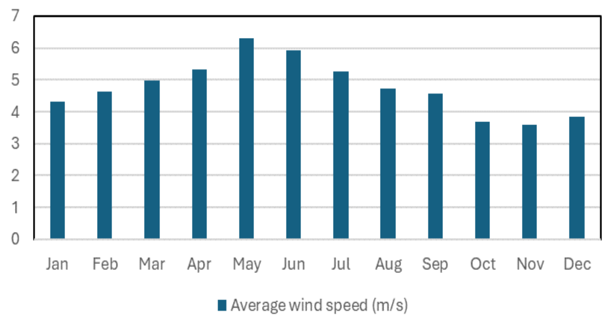


Fig. 4. Monthly average daily wind speed selected area. Data from (NASA).

Fig. 5 illustrates a hybrid energy system layout for a household with a daily energy need of 11.25 kWh and a peak demand of 2.80 kW. It shows the energy flow, detailing how various components work together to meet the household's energy requirements efficiently. It details the roles of various energy resources, including the photovoltaic (PV) system, wind turbine system, batteries, and grid connections. The diagram illustrates how energy is generated, stored, and utilized, ensuring a reliable supply of power while optimizing the use of available resources.

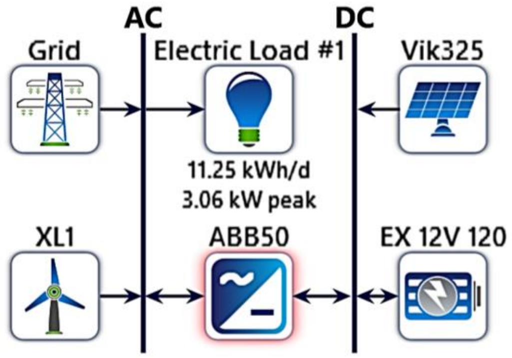


Fig. 5. The proposed grid connected HRES.

Table 4. Components of the proposed grid connected HRES.

Component	Name	Size	Unit
PV	Vikram Solar325Eldora VSP.72.325.03	12.0	kW
Storage	Excide 12V 120AH	1	strings
Wind turbine	Bergey BWC XL.1	1	ea.
System converter	ABB PVI-CENTRAL-50-US (480V)	8.50	kW
Grid	Grid	999,999	kW

3.2 Economic Analysis

3.2.1 Total net present cost (NPC)

The equation for NPC is as follows:

$$NPC = \sum_{i=1}^{t} i_d (C_{cap} + C_{rep} + C_{OM} + C_{fuel} - C_{sellback}) \quad (1)$$

where i_d is discount factor, C_{cap} represents capital cost, C_{rep} is replacement cost, C_{OM} is operational & maintenance cost, C_{fuel} is fuel cost and $C_{sellback}$ is sellback cost. [30]

The equation for discount factor (id) is as follows:

$$i_d = \frac{1}{(1+i)^n} \quad (2)$$

where i is real discount rate (%), and n represents number of years. i can be calculated as follows:

$$i = \frac{i' - f}{i + f} \quad (3)$$

where i' represent nominal discount rate and f is inflation rate.

The equation for annual cost (C_{ann}) is as follows:

$$C_{ann} = CRF(i,n) \times NPC \quad (4)$$

where CRF(i, n) is:

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (5)$$

Enter the technical and financial information for each MG component to configure the system in HOMER Pro. Indicate the dimensions, capacity, cost, efficiency, and other pertinent details of the energy storage, RES, and other system design elements. The HOMER software then uses optimization analysis to identify the best system setup and operation plan that, given the specified system characteristics, minimizes the NPC. The present value of a future expense or benefit after taking the system lifetime and discount rate into account is known as the present value of NPC. The NPC value will be given by HOMER directly.

3.2.2 Levelized cost of energy (LCOE):

The following is the formula used to determine the LCOE:

$$LCOE = \frac{(C_{ann} - C_{boiler} H_{served})}{E_{served}} \tag{6}$$

where C_{boiler} is the boiler marginal cost per kWh, H_{served} represents the total thermal load served per year (kWh/yr), and E_{served} is the total electrical load served per year (kWh/yr).
The E_{served} is the sum of energy used to meet both primary and deferrable loads throughout the year, in addition to the energy sold to the grid. The following is the formula used to determine the E_{served}.

$$E_{served} = E_{served,AC} + E_{served,DC} + E_{served,def} + E_{served,sales} \tag{7}$$

where $E_{served,AC}$ is the AC primary load served per year (kWh/yr), $E_{served,DC}$ represents the DC primary load served per year (kWh/yr), $E_{served,def}$ is the deferrable load served per year (kWh/yr) and $E_{served,sales}$ is the energy sold to the grid per year (kWh/yr).

3.2.3 Component cost:

Table 5 provides a breakdown of the NPC for each component of the proposed grid-connected HRES. The photovoltaic (PV) module, Vikram Solar, has the highest NPC at ₹427,721, primarily due to its significant capital and operating costs. The wind turbine, Bergey BWC XL.1, also contributes substantially with an NPC of ₹142,692, driven by high capital, operating, and replacement costs. The converter (ABB PVI-CENTRAL) and battery storage (Excide 12V 120AH) have moderate NPCs of ₹58,225 and ₹16,323, respectively. Notably, the grid component shows a negative NPC of -₹205,768, indicating cost savings or revenue from selling energy back to the grid. Overall, the total system NPC is ₹439,193, reflecting the combined costs of all components, with the PV module and wind turbine being the most significant contributors to the overall cost.

Table 5. NPC of each component of the proposed system.

Name	Capital	Operating	Salvage	Resource	Replacement	Total
Vikram Solar325Eldora VSP.72.325.03	₹336,000	₹91,721	₹0.00	₹0.00	₹0.00	₹427,721
Bergey BWC XL.1	₹103,587	₹28,277	-₹14,873	₹0.00	₹25,701	₹142,692
ABB PVI-CENTRAL-50-US (480V)	₹42,556	₹0.00	-₹3,879	₹0.00	₹19,549	₹58,225
Excide 12V 120AH	₹13,969	₹4,767	-₹2,412	₹0.00	₹0.00	₹16,323
Grid	₹0.00	-₹205,768	₹0.00	₹0.00	₹0.00	-₹205,768
System	₹496,112	-₹81,004	-₹21,165	₹0.00	₹45,250	₹439,193

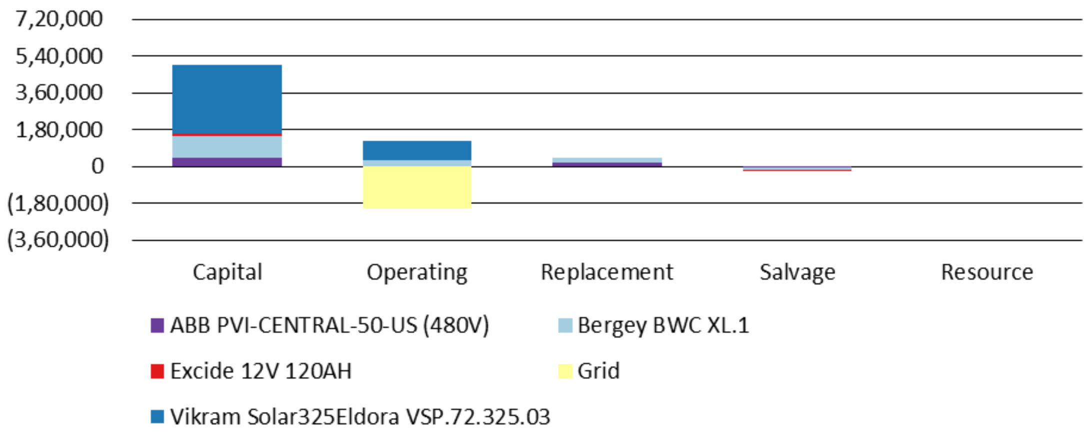


Fig. 6. NPC of each component.

Table 6. Annualized cost of each component of the proposed system.

Name	Capital	Operating	Salvage	Replacement	Resource	Total
Vikram Solar325Eldora VSP.72.325.03	₹24,617	₹6,720	₹0.00	₹0.00	₹0.00	₹31,337
Bergey BWC XL.1	₹7,589	₹2,072	-₹1,090	₹1,883	₹0.00	₹10,454
ABB PVI-CENTRAL-50-US (480V)	₹3,118	₹0.00	-₹284.23	₹1,432	₹0.00	₹4,266
Excide 12V 120AH	₹1,023	₹349.23	-₹176.74	₹0.00	₹0.00	₹1,196
Grid	₹0.00	-₹15,076	₹0.00	₹0.00	₹0.00	-₹15,076
System	₹36,348	-₹5,935	-₹1,551	₹3,315	₹0.00	₹32,178

Table 6 details the annualized costs for each component of the proposed grid-connected HRES, breaking down expenses into capital, operating, replacement, salvage, and total costs. The photovoltaic (PV) module, Vikram Solar, incurs the highest annualized cost at ₹31,337, driven by significant capital and operating expenses. The wind turbine, Bergey BWC XL.1, follows with an annualized cost of ₹10,454, which includes substantial capital, operating, and replacement costs, offset slightly by the salvage value. The converter (ABB PVI-CENTRAL) has a moderate annualized cost of ₹4,266, while the battery storage (Excide 12V 120AH) shows the lowest annualized cost at ₹1,196. Notably, the grid component reflects a negative annualized cost of -₹15,076, indicating a net financial benefit from reduced grid usage or energy sales. Overall, the system's total annualized cost is ₹32,178, which accounts for all components, with the PV module being the most significant contributor to ongoing costs, while the grid connection provides a cost-saving benefit.

3.3 Technical Analysis

3.3.1 Electrical summary

Table 7 provides an overview of the electrical performance, focusing on excess electricity production, unmet electric load, and capacity shortage. The system generates 279 kWh of excess electricity annually, indicating that it produces more energy than needed, which can be sold back to the grid or stored. Importantly, the system has an unmet electric load of 0 kWh per year, meaning it fully meets the household's energy demands without any shortfall. Additionally, there is no capacity shortage, as the system's generation capacity is sufficient to handle peak loads without deficiencies.

Table 7. Electrical summary including excess electricity and unmet electric load.

Quantity	Value (kWh/yr)
Excess Electricity	279
Shortage Capacity	0
Unmet Electric Load	0

3.3.2 Energy production & consumption summary

Table 8 provides a detailed breakdown of the annual energy production for each system component, highlighting the contributions from solar, wind, and grid energy. The Vikram Solar PV module serves as the main energy source, producing 18,782 kWh annually and accounting for 80.2% of the total energy output. The wind turbine, Bergey BWC XL.1, contributes 2,287 kWh annually, making up 9.77% of the total. Grid purchases account for the remaining 10%, with 2,349 kWh supplied by the grid to meet the household's energy needs. This distribution highlights the system's strong reliance on solar power, with wind energy providing additional support, and the grid acting as a minor supplementary source.

Table 8. Energy production in the proposed system.

Component	Production (kWh/yr)	Percent
Vikram Solar325Eldora VSP.72.325.03	18,782	80.2
Bergey BWC XL.1	2,287	9.77
Grid Purchases	2,349	10.0
Total	23,418	100

Table 9 outlines the annual energy consumption distribution within the system, highlighting how the generated energy is utilized. The AC primary load, which represents the household's direct electricity usage, consumes 4,105 kWh per year, accounting for 18.5% of the total energy consumption. There is no energy consumption attributed to DC primary or deferrable loads, indicating that all direct energy use is in AC form. A significant portion of the energy, 81.5%, or 18,107 kWh, is sold back to the grid, reflecting the system's ability to generate more electricity than the household consumes.

Table 9. Energy consumption in the proposed system.

Component	Consumed Energy (kWh/yr)	Percent
Grid (Sales)	18,107	81.5
AC Load	4,105	18.5
DC Load	0	0
Deferrable Load	0	0
Total	22,212	100

3.3.3 Performance metrics

Table 10 provides detailed technical specifications for the wind turbine system within the energy setup. The wind turbine has a rated capacity of 1.00 kW and operates for 6,849 hours per year. Its output fluctuates, ranging from 0 kW during periods of no wind to a peak of 1.24 kW under optimal wind conditions. The average output is 0.261 kW, corresponding to a capacity factor of 26.1%, which measures the turbine's efficiency in converting wind energy into electricity. Wind penetration, representing the proportion of wind energy in the total energy mix, stands at 55.7%, highlighting its substantial contribution to the overall renewable energy system. The turbine produces a total of 2,287 kWh per year, with a levelized cost of 4.57 ₹/kWh, demonstrating a relatively low cost of energy generation from wind.

Table 10. Technical specification of wind turbine system.

Quantity	Value
Minimum Output Power	0 kW
Maximum Output Power	1.24 kW
Rated Capacity	1.00 kW
Average Output Power	0.261 kW
Wind Penetration	55.7 %
Annual Hours of Operation	6,849 hrs/yr
Levelized Cost	4.57 ₹/kWh
Capacity Factor	26.1 %
Total Energy Production	2,287 kWh/yr

Table 11 provides the technical specifications of the converter within the energy system, highlighting its performance and efficiency. The converter operates for 4,264 hours annually, converting 18,502 kWh of energy input into 17,576 kWh of energy output, with losses amounting to 925 kWh per year. This indicates that the converter operates with a certain degree of inefficiency, but still effectively manages the energy flow between the various system components. The converter has a capacity of 8.50 kW, with a mean output of 2.01 kW, reflecting its typical operational level. It can vary its output from a minimum of 0 kW, when not in use, to a maximum of 8.50 kW under peak demand conditions.

Table 11. Technical specification of converter.

Quantity	Value
Energy Out	17,576 kWh/yr
Energy In	18,502 kWh/yr
Energy Losses	925 kWh/yr
Rated Capacity	8.50 kW
Minimum Output Power	0 kW
Maximum Output Power	8.50 kW
Average Output Power	2.01 kW
Annual Hours of Operation	4,264 hrs/yr
Capacity Factor	23.6 %

4. RESULT ANALYSIS

Case 1: This scenario features a system with 12 kW of photovoltaic (PV) power and no wind power. The system relies on 8.56 kW of conventional power. The NPC is ₹412,284.6 with a COE of ₹1.4681/kWh. The annual operating cost is relatively low at ₹2,457.08, and the initial capital investment is ₹378,748.2. The renewable fraction stands at 85.14%, indicating a high proportion of energy comes from renewable sources. This configuration offers a good balance between cost and renewable energy utilization.

Case 2: In this setup, the system again uses 12 kW of PV power with no wind power but has a slightly higher conventional power requirement of 8.57 kW. The NPC is ₹421,309.2, and the COE is slightly higher at ₹1.5003/kWh. The operating cost is lower than in Case 1 at ₹2,083.93 annually, but the initial capital is higher at ₹392,865.9. The renewable fraction is marginally better at 85.46%. This configuration improves renewable energy contribution slightly but comes at a higher cost.

Case 3: This case introduces 1 kW of wind power along with 12 kW of PV and 8.57 kW of conventional power. The NPC increases to ₹428,841, but the COE decreases to ₹1.4130/kWh, making it more cost-effective per unit of energy produced. The operating cost is negative at -₹3,929.55/year, suggesting financial benefits or savings from the wind component. The initial capital required is ₹482,475.1, and the renewable fraction rises to 89.21%. This case is more cost-efficient and has a higher renewable energy share due to the wind power addition.

Case 3: This case introduces 1 kW of wind power along with 12 kW of PV and 8.57 kW of conventional power. The NPC increases to ₹428,841, but the COE decreases to ₹1.4130/kWh, making it more cost-effective per unit of energy produced. The operating cost is negative at -₹3,929.55/year, suggesting financial benefits or savings from the wind component. The initial capital required is ₹482,475.1, and the renewable fraction rises to 89.21%. This case is more cost-efficient and has a higher renewable energy share due to the wind power addition.

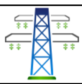
Case 4: This scenario is similar to Case 3 but with a slight adjustment in conventional power to 8.50 kW and a marginally higher initial capital of ₹496,112. The NPC is ₹439,193 and the COE is ₹1.4486/kWh. The operating cost is negative at -₹4,170.23/year, indicating cost savings. The renewable fraction is 89.43%, slightly better than Case 3. This configuration offers a higher renewable fraction and cost benefits but requires a higher initial investment.

Case 5: In this configuration, the system has no PV or wind power, relying entirely on 12 kW of conventional power. The NPC is ₹466,443.5, with a very high COE of ₹6.6274/kWh. The annual operating cost is significantly high at ₹26,585.04, while the initial capital is relatively low at ₹103,587. The renewable fraction is very low at 44.36%, making this setup the least favorable in terms of renewable energy use and cost efficiency.

Case 6: This case is similar to Case 5 but with a higher NPC of ₹481,483 and a COE of ₹6.8411/kWh. The operating cost is slightly higher at ₹26,661.94, and the initial capital is ₹117,577. The renewable fraction remains the same as in Case 5 at 44.36%. This case also relies entirely on conventional power, with similar drawbacks in terms of cost and renewable energy contribution.

Case 7: This configuration involves no PV or wind power and has no conventional power generation. The NPC is ₹504,292.6, with a very high COE of ₹9.0000/kWh. The operating cost is ₹36,947.5/year, and the initial capital is zero. The renewable fraction is almost negligible at 4.88E-13%, making this case the least favorable in every aspect, as it provides no actual energy production.

Table 12. Optimization results of hybrid system.

					PV (kW)	Wind (kW)	Conv. (kW)	NPC (₹)	COE (₹/kWh)	Operating cost (₹/year)	Initial capital (₹)	Renewable Fraction (%)
	-	-			12	-	8.56	412284.6	1.468097	2457.078	378748.2	85.13686
	-				12	-	8.57	421309.2	1.500321	2083.927	392865.9	85.45839
		-			12	1	8.57	428841	1.413043	-3929.554	482475.1	89.21211
					12	1	8.50	439193	1.448642	-4170.228	496112	89.42606
-		-		-	-	1	-	466443.5	6.62741	26585.04	103587	44.35862
-					-	1	0.00420	481483	6.841098	26661.94	117577	44.35862
-	-	-		-	-	-	-	504292.6	9	36947.5	0	4.88E-13
-	-				-	-	0.0160	519413	9.269852	37025.99	14049.18	4.88E-13

Comparison and Recommendation:

Among the cases, Cases 3 and 4 stand out as the most balanced options. They both include wind power, which reduces the COE and increases the renewable fraction, offering better cost efficiency and a higher share of renewable energy. Case 4 has a slightly higher renewable fraction and better operating cost benefits compared to Case 3, albeit with a higher initial capital.

Cases 5, 6, and 7 are less favorable due to their reliance on conventional power, which results in high COE, operating costs, and low renewable fractions. Among these, Case 7 is the least desirable as it offers no practical energy output.

Recommendation: Case 4 is the best option due to its high renewable fraction, lower COE, and cost savings, despite requiring a higher initial investment. It provides a good balance between renewable energy utilization and overall-cost-effectiveness.

4.1 Compare Economics Result

Table 13 compares the performance of a base system using conventional (nonrenewable) energy against a proposed renewable energy system. The base system has a Net Present Cost (NPC) of ₹504,293, while the proposed system's NPC is lower at ₹439,193, indicating cost savings. The base system has no initial capital expenditure (CAPEX) but has very high annual operating expenses (OPEX) of ₹36,948. In contrast, the proposed system requires a CAPEX of ₹496,112 but has negative OPEX of -₹4,170, reflecting savings or income, likely due to subsidies or reduced operational costs. The Levelized Cost of Energy (LCOE) is significantly lower in the proposed system at ₹1.45 per kWh compared to ₹9.00 per kWh for the base system. Additionally, the proposed system emits less CO2 annually (1,484 kg) compared to the base system (2,595 kg), demonstrating a lower environmental impact. Both systems show zero fuel consumption, indicating no direct reliance on fossil fuels. Overall, the proposed renewable energy system is more cost-effective, environmentally friendly, and economically advantageous compared to the conventional base system.

Table 13. Comparison of renewable versus nonrenewable energy system.

	Base System	Proposed System
Net Present Cost (₹)	504,293	439,193
CAPEX (₹)	0.00	496,112
OPEX (₹)	36,948	-4,170
LCOE (₹/kWh)	9.00	1.45
CO2 Emitted (kg/yr)	2,595	1,484
Fuel Consumption (L/yr)	0	0

5. CONCLUSION

This study provides a detailed economic and technical analysis of a hybrid solar and wind energy microgrid system, demonstrating its feasibility and benefits. The integration of solar PV system and wind turbines within the microgrid framework proves to be both cost-effective and efficient in meeting energy demands. The economic analysis shows significant potential for cost savings through reduced Total NPC and LCOE compared to traditional energy sources. Technically, the system exhibits high reliability and efficiency, with balanced energy production and consumption.

Our findings underscore the importance of adopting HRES to enhance energy security and sustainability. By leveraging the strengths of both solar and wind energy, the proposed microgrid system offers a robust solution for future energy needs. Policymakers and stakeholders are encouraged to support the development and implementation of such systems through favourable policies and investment. This transition to renewable energy not only addresses environmental concerns but also provides economic advantages, paving the way for a sustainable energy future.

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