Integrated Assessment of Hybrid Renewable Energy Systems with Diverse Storage Solutions: Techno-Economic and Environmental Perspectives

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Abstract:
The growing imperative for sustainable energy solutions has driven significant advancements in Hybrid Renewable Energy Systems (HRES), which combine multiple renewable generation technologies with integrated storage capabilities. This study presents a comprehensive evaluation of various HRES configurations incorporating lithium-ion batteries, hydrogen storage, pumped hydro systems, and thermal storage solutions, examining their technical performance, economic feasibility, and environmental benefits through a multi-dimensional analytical framework. The research methodology employs techno-economic assessment using key metrics such as Levelized Cost of Energy and Net Present Value, complemented by environmental impact analysis quantifying emission reductions and lifecycle sustainability. The findings demonstrate that strategic integration of complementary renewable sources with appropriately sized storage solutions effectively addresses intermittency challenges while optimizing resource utilization. These systems not only improve energy security and grid independence but also deliver measurable economic and environmental advantages compared to conventional alternatives. The study provides valuable insights for energy policymakers developing transition strategies, infrastructure planners designing resilient power systems, and researchers advancing storage technologies. Importantly, the analytical framework developed can be adapted to various geographical contexts and demand profiles, offering a scalable approach to sustainable energy deployment. This research contributes to the ongoing global energy transition by demonstrating how hybrid renewable systems can simultaneously meet reliability, affordability, and sustainability objectives, while identifying key considerations for their effective implementation across different operational scenarios.

Keywords: HRES, Renewable energy, storage solution, cost of energy.

Introduction:

The contemporary power sector is experiencing a fundamental restructuring as nations seek to reduce carbon emissions, expand energy accessibility, and establish sustainable infrastructure. Historical reliance on fossil fuels has created environmental challenges through greenhouse gas accumulation while exposing energy networks to supply uncertainties and geopolitical risks. Within this transition, renewable generation technologies including photovoltaic, wind, hydroelectric, and bioenergy systems have become foundational elements of modern energy strategies [1-4]. A critical limitation of standalone renewable installations stems from their unpredictable generation patterns dictated by meteorological and geographic factors. Photovoltaic output fluctuates with daylight availability and seasonal variations, while wind turbine productivity depends on location-specific air currents. These inconsistencies create supply-demand mismatches that compromise grid stability, particularly in areas with underdeveloped transmission infrastructure. Integrated Hybrid Renewable Energy Systems address these constraints by combining multiple generation technologies with reserve capacity mechanisms and storage solutions. These composite systems capitalize on the synergistic relationships between different renewable sources. Solar and wind installations demonstrate diurnal complementarity, whereas biomass and hydro facilities can provide controllable generation capacity [5-8]. Nevertheless, even optimized hybrid configurations necessitate storage components to mitigate transient fluctuations, retain excess production, and maintain supply-demand equilibrium. While conventional systems predominantly employed electrochemical storage, contemporary solutions incorporate diverse technologies including lithium-ion accumulators, hydrogen-based storage, thermal reservoirs, and pumped hydroelectric facilities, each offering distinct technical and operational advantages.

The incorporation of multiple storage modalities within hybrid systems represents a fundamental evolution in energy architecture. Composite storage strategies enhance operational flexibility, system resilience, and overall efficiency by accommodating variable input and load profiles. Lithium-ion batteries excel in rapid-response applications, hydrogen systems enable extended-duration storage with reconversion potential, while pumped hydro and thermal solutions provide economical large-capacity alternatives where geographical conditions permit. Comprehensive evaluation of these integrated systems requires simultaneous technical, economic, and environmental assessment. Performance analysis incorporates metrics such as energy conversion efficiency, normalized generation costs (LCOE), discounted cash flow valuation (NPV), investment recovery periods, and cost-benefit ratios critical parameters for financial stakeholders and regulatory bodies [9,10]. Environmental appraisal focuses on emission abatement potential, carbon footprint reduction, spatial requirements, and full lifecycle impacts, aligning with global climate objectives and sustainability benchmarks.

Sophisticated computational tools including HOMER Energy, MATLAB/Simulink, and RETScreen enable detailed modeling of these complex systems under variable operating conditions [11-15]. These platforms facilitate comparative scenario analysis, parameter sensitivity testing, and optimization of system architectures to achieve balanced economic, reliability, and sustainability outcomes. Notwithstanding these advantages, implementation barriers persist including substantial capital requirements, technical complexity, operational maintenance demands, inconsistent regulatory frameworks, and absence of standardized protocols. Further research imperatives include hybrid system topologies, intelligent energy management protocols, and location-specific feasibility assessments to enable widespread deployment. Addressing these challenges through coordinated policy development, technological innovation, and financial mechanisms will be essential for realizing the full potential of advanced hybrid renewable systems in global energy transition efforts.

Site Selection and Input Credentials

The suburban locality of Hoskerhalli in southern Bangalore (Karnataka) as represented in Figure 1 serves as the primary research site for evaluating the proposed hybrid energy system. This location presents an exemplary case for examining decentralized renewable energy integration.

Figure 1: Hosakerehalli, a small town in Bangalore, Karnataka, India.

The electrical load characteristics as mentioned in Figure 2 to 6 of Hoskerhalli exhibit distinct temporal variations that are crucial for system design. Figure X presents a detailed breakdown of power consumption across multiple time dimensions, revealing important patterns for energy system planning.

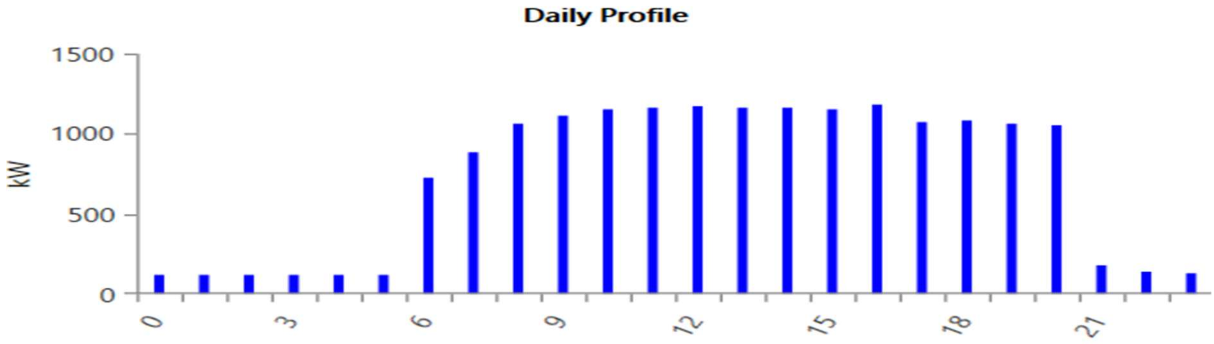

Figure 2: Daily load profile for the selected site

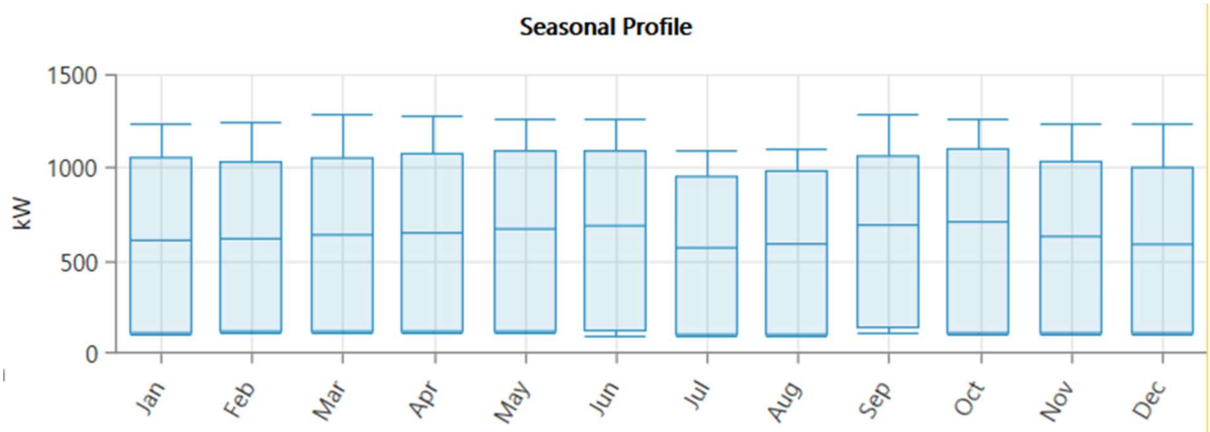

Figure 3: Seasonal load profile for the chosen location

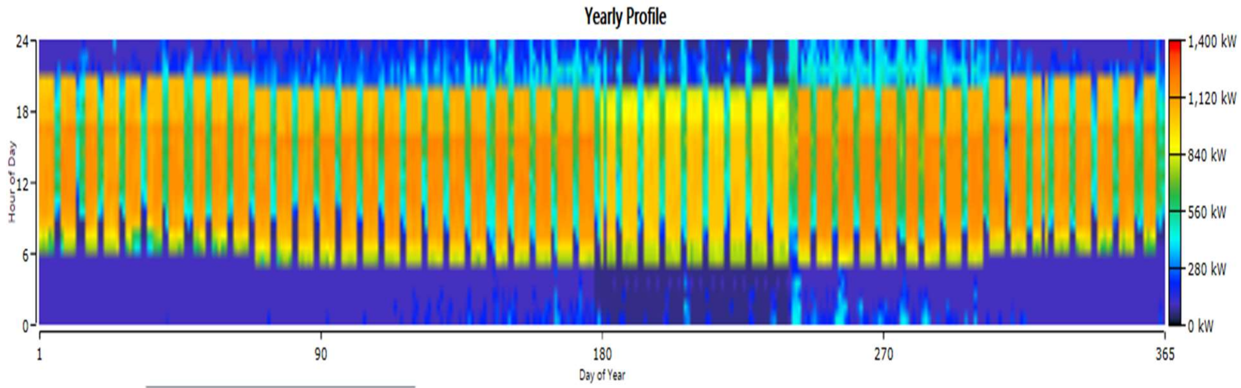

Figure 4: Yearly load profile for the selected site

Metric	Baseline	Scaled
Average (kWh/day)	15,382.	15,382.
Average(kW)	640.96	640.96
Peak (kW)	1,287.7	1,287.7
Load factor	.5	.5

Figure 5: configuration for the load profile

Hour	Load (kW)
0	118.3
1	118.29
2	118.27
3	118.26
4	119.58
5	119.38
6	726.94
7	880.86
8	1,058.58
9	1,115.91
10	1,149.54
11	1,162.49
12	1,172.03
13	1,158.46
14	1,160.5
15	1,153.63
16	1,183.25
17	1,077.24

Figure 6: Electrical load profile for the site in Banglore, India

Result and Discussion

This section examines the comprehensive simulation results of the hybrid renewable energy system's technical, economic, and environmental performance. The system model, developed in HOMER software, integrates multiple energy components including solar PV arrays, wind turbines, diesel backup generators, grid connection, lithium-ion battery banks, and pumped hydro storage. Through detailed simulation studies, we evaluate the system's operational effectiveness, financial viability, and ecological impact under different seasonal conditions and demand scenarios. Our investigation focuses on several critical aspects of system performance. First, we analyze the technical feasibility by examining energy generation patterns from each renewable source and their temporal complementarity. The economic assessment considers both capital and operational expenditures, with particular attention to the net present cost and levelized cost of energy. Environmental impact is quantified through emissions analysis, comparing the hybrid system's carbon footprint against conventional alternatives. The study also explores how the integrated storage systems affect grid independence and power reliability, particularly during periods of renewable resource variability.

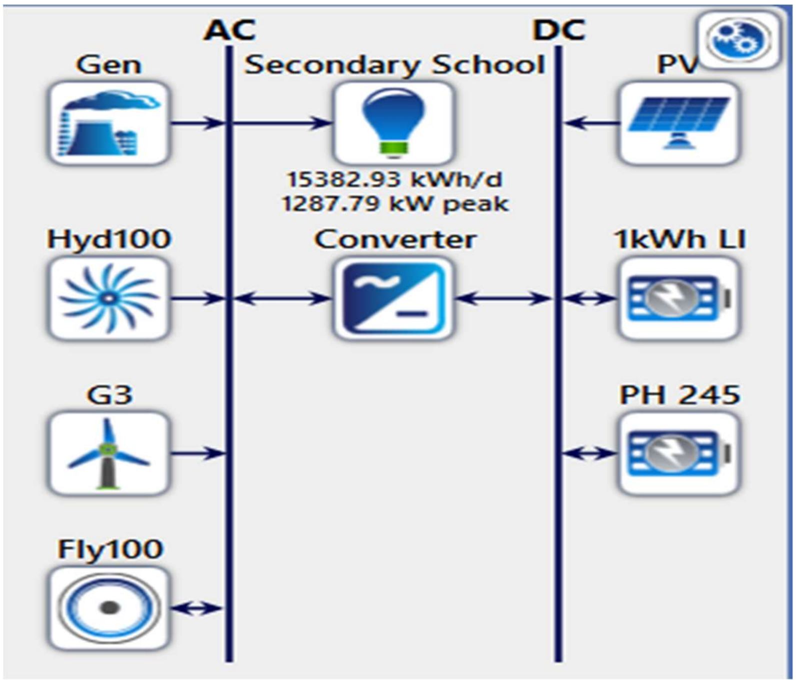

Figure 7: Representation of the proposed system consisting of PV, wind, hydro, converter. Diesel, pumped hydro, battery and flywheel storage system

Figure 7 presents the schematic layout of the hybrid renewable energy system specifically designed to power a secondary school in the study area. The system features an innovative dual-bus architecture that efficiently manages both AC and DC power flows through a central bi-directional converter, enabling seamless integration of diverse energy sources and storage technologies to meet the facility's substantial daily energy requirement of 15,382.93 kWh with a peak demand of 1,287.79 kW. The DC subsystem incorporates a 250 kW solar photovoltaic array that directly feeds the DC bus, along with two complementary energy storage solutions: a 1 kWh lithium-ion battery bank for rapid response to short-term load fluctuations, and a Pumped Hydro 245 system designed for bulk energy storage and time-shifting of surplus renewable generation. The AC network combines conventional and renewable generation assets, including a 100 kW backup diesel generator for reliability during extended low-renewable periods, a 100 kW hydro turbine that leverages seasonal water flow variations, and a 3 kW wind turbine that contributes during high-wind conditions. A 100 kW flywheel energy storage unit provides critical grid stabilization services by addressing transient power quality issues and rapid load changes.

Table 1: Optimal sizing and cost assessment of different HRES with multiple renewable and storage systems

Architecture									Cost				System	
PV (kW)	G3	Gen (kW)	1kWh LI	PH 245	Fly100	Hyd100 (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
3,310	20	1,500		63	0	98.1	1,321	LF	$16.8M	$0.232	$403,375	$11.6M	90.8	144,613
3,419		1,500		64	0	98.1	1,311	LF	$16.9M	$0.232	$409,882	$11.6M	90.4	151,803
3,341	26	1,500		58	1	98.1	1,220	LF	$17.1M	$0.235	$395,936	$12.0M	90.8	144,419
3,425		1,500		58	1	98.1	1,212	LF	$17.1M	$0.236	$417,366	$11.7M	89.6	163,943
3,565	187			116	0	98.1	1,317	CC	$20.4M	$0.282	$367,771	$15.7M	100	0
2,105		1,500	1,980		0	98.1	1,299	CC	$20.8M	$0.286	$992,972	$7.95M	56.3	633,079
2,097	12	1,500	2,006		0	98.1	1,420	CC	$20.8M	$0.287	$978,290	$8.20M	57.2	619,549
3,628	211			106	1	98.1	1,385	CC	$21.0M	$0.290	$359,567	$16.4M	100	0
2,131		1,500	1,823		1	98.1	1,210	CC	$21.2M	$0.291	$1.00M	$8.20M	56.1	636,327
2,066	24	1,500	1,891		1	98.1	1,211	CC	$21.2M	$0.291	$978,247	$8.51M	57.6	613,613
5,562				161	0	98.1	1,950	CC	$23.9M	$0.329	$415,208	$18.5M	100	0
	24	1,500		27	0	98.1	510	CC	$25.1M	$0.346	$1.76M	$2.39M	13.0	1,261,262
		1,500		26	0	98.1	489	CC	$25.1M	$0.346	$1.79M	$1.93M	10.3	1,299,322
	37	1,500		23	1	98.1	478	CC	$25.4M	$0.349	$1.74M	$2.83M	14.1	1,246,934
		1,500		23	1	98.1	451	CC	$25.4M	$0.350	$1.80M	$2.15M	9.82	1,305,928
	76	1,500	762		0	98.1	521	CC	$25.5M	$0.351	$1.73M	$3.15M	20.2	1,174,659
		1,500	797		0	98.1	497	CC	$25.6M	$0.353	$1.84M	$1.80M	12.0	1,289,321
	72	1,500	696		1	98.1	446	CC	$25.9M	$0.357	$1.75M	$3.32M	19.3	1,186,952
		1,500	724		1	98.1	466	CC	$26.1M	$0.359	$1.86M	$2.05M	11.4	1,296,900

The hybrid renewable energy system was meticulously modeled and analyzed using HOMER simulation software, incorporating photovoltaic arrays, wind turbines, hydroelectric generators, diesel backup systems, and three distinct energy storage technologies. The study evaluated various system architectures employing both load-following and cycle-charging operational strategies, with comprehensive assessment of technical, economic, and environmental performance metrics including net present cost, levelized energy costs, renewable penetration rates, and fuel requirements.

Photovoltaic capacity demonstrated significant variation across scenarios, ranging from 2,066 kW to 5,562 kW, with larger arrays directly correlating with increased renewable energy contribution. The most sustainable configuration achieved complete energy independence through a 5,562 kW solar array coupled with 161 units of pumped hydro storage, eliminating fossil fuel consumption entirely. The diesel generator maintained a consistent 1,500 kW capacity across configurations, serving primarily as backup during renewable generation shortfalls.

Energy storage implementation showed substantial diversity:

- Lithium-ion battery banks (0-2,006 units)

- Flywheel storage systems (selectively incorporated)
- Pumped hydro storage (23-161 units)

These storage solutions effectively mitigated renewable intermittency, with configurations featuring greater storage capacity demonstrating superior performance in reducing fuel dependence and enhancing sustainability. The hydroelectric component remained fixed at 98.1 kW, providing consistent baseload support, while power converter capacity varied considerably (446 kW to 1,950 kW) to accommodate different power flow requirements.

Economic and Environmental Performance

Financial analysis indicated:

- Net present costs spanning \$16.8M to \$26.1M
- Levelized energy costs between \$0.232/kWh and \$0.359/kWh
- Annual operating expenses ranging from \$359,567 to over \$1M
- Initial capital requirements from \$1.80M to \$18.5M

Environmental metrics showed:

- Renewable contribution varying from 9.82% to 100%
- Annual fuel consumption between zero and 1.2 million liters
- Clear correlation between storage integration and emission reductions

Recommended Optimal Configuration

The most balanced system configuration features:

- 3,310 kW photovoltaic capacity
- 20 kW wind generation
- 1,500 kW diesel backup
- 63 pumped hydro storage units
- 98.1 kW hydroelectric capacity
- 1,321 kW power conversion system
- Load-following dispatch strategy

This optimized design achieves outstanding performance metrics:

- \$16.8M net present cost
- \$0.232/kWh energy cost
- 90.8% renewable fraction
- 144,613 liters annual fuel consumption

The selected configuration represents an ideal compromise between economic viability and environmental sustainability, demonstrating how carefully engineered hybrid systems can substantially reduce fossil fuel dependence while maintaining cost-effectiveness. The comprehensive analysis provides valuable insights for implementing similar renewable energy solutions in comparable environments.

Table 2: Cost summary for the proposed system

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	$750,000.00	$317,111.59	$579,411.29	$1,869,490.51	-$61,087.25	$3,454,926.14
Generic 245kWh Pumped Hydro	$1,386,000.00	$44,748.08	$1,628,867.09	$0.00	-$3,234.03	$3,056,381.14
Generic 3 kW	$360,000.00	$114,770.65	$46,539.06	$0.00	-$64,680.62	$456,629.09
Generic flat plate PV	$8,274,417.41	$0.00	$427,870.67	$0.00	$0.00	$8,702,288.08
Generic Hydro 100kW	$459,845.00	$0.00	$178,335.09	$0.00	$0.00	$638,180.09
System Converter	$396,315.63	$168,146.35	$0.00	$0.00	-$31,646.84	$532,815.14
System	$11,626,578.03	$644,776.66	$2,861,023.20	$1,869,490.51	-$160,648.74	$16,841,219.66

The comprehensive economic assessment of the hybrid renewable energy system reveals distinct cost structures across different components. The diesel generator, while having a moderate initial investment of $750,000, accumulates substantial long-term expenses totaling $3.45 million over its lifespan. These costs stem primarily from frequent maintenance ($579,411) and significant fuel expenditures ($1.87 million), making it the most expensive component operationally. The negative salvage value (-$61,087) further underscores its economic limitations compared to renewable alternatives.

Pumped hydro storage presents a different financial profile, with a considerable capital outlay of $1.39 million but minimal replacement needs ($44,748). Its operational costs total $1.63 million, reflecting the maintenance requirements of hydro-mechanical systems, but it eliminates fuel expenses entirely. The wind turbine system shows favorable economics with $360,000 initial investment and modest operating costs ($46,539), totaling $456,629 lifetime expenditure, demonstrating the cost-effectiveness of wind energy integration.

The photovoltaic array represents the largest capital investment at $8.27 million, yet requires only $427,871 in maintenance over its operational life with no fuel or replacement costs. The hydroelectric component follows a similar pattern with $459,845 initial cost and $178,335 in maintenance, totaling $638,180. The power converter system completes the financial picture with $396,316 capital cost and $168,146 replacement value, amounting to $532,815 overall.

4.4 Aggregate System Economics

The complete hybrid system requires $16.84 million in total expenditures, distributed as:

- Initial capital: $11.63 million (69% of total)
- Ongoing operations: $2.86 million (17%)
- Fuel costs: $1.87 million (11%)
- Equipment replacement: $644,777 (4%)

This financial breakdown highlights several key insights:

1. Renewable components dominate capital costs but minimize recurring expenses
2. Conventional generation accounts for disproportionate operational costs
3. Storage technologies balance upfront investment with long-term benefits
4. The system achieves cost diversification across different expenditure categories

The analysis demonstrates how renewable energy systems transition costs from variable operational expenses to fixed capital investments, with the financial burden front-loaded but operational savings accruing over time. This cost structure, while requiring significant initial funding, ultimately delivers superior economic and environmental returns compared to conventional energy systems. The negative salvage values across components reflect the challenging economics of repurposing or reselling specialized energy equipment at project conclusion.

Production	kWh/yr	%
Generic flat plate PV	5,359,050	79.3
Autosize Genset	514,881	7.62
Generic 3 kW	131,725	1.95
Hydro	750,905	11.1
Total	6,756,561	100

Consumption	kWh/yr	%
AC Primary Load	5,614,769	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	5,614,769	100

Quantity	kWh/yr	%
Excess Electricity	545,886	8.08
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	90.8	%
Max. Renew. Penetration	1,980	%

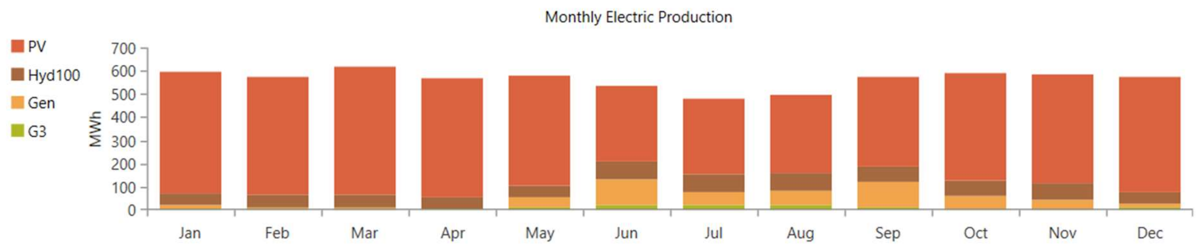

Figure 8: Electrical profile for the proposed system

The hybrid renewable energy system demonstrates robust performance in meeting the annual electricity demand of 5,614,769 kWh, with total generation reaching 6,756,561 kWh per year. This surplus production ensures complete load satisfaction without any power shortages, confirming the system's optimal sizing and reliable operation. The energy mix reveals a strategic combination of renewable sources, with solar photovoltaic arrays contributing the majority share at 5,359,050 kWh annually (79.3% of total output). This substantial solar contribution capitalizes on the location's favorable insolation conditions while maintaining consistent year-round performance.

Complementary renewable sources provide important balancing capacity to the system. The hydroelectric unit delivers 750,905 kWh annually (11.1%), offering valuable dispatchable generation during periods of reduced solar output. Wind power makes a modest contribution of 131,725 kWh (1.95%), primarily supplementing evening and early morning demand. The diesel backup system, generating 514,881 kWh (7.62%), plays a crucial reliability role during extended periods of low renewable availability, though its operation is minimized to maintain system sustainability.

Conclusion

This research conducted a comprehensive evaluation of a standalone hybrid renewable energy system combining solar PV, hydroelectric, wind, and diesel generation with battery storage. The study successfully demonstrated the technical and economic feasibility of implementing such systems in off-grid communities through detailed modeling using HOMER software. The optimized configuration reliably met the annual electricity demand of 5,614,769 kWh without any power shortages, while achieving a remarkable 90.8% renewable energy penetration.

The financial analysis revealed a total project cost of $16.84 million over the system lifespan, with solar PV infrastructure representing the largest capital expenditure at $8.27 million. Despite significant upfront investments, the renewable components demonstrated superior long-term economics due to minimal operational costs compared to the diesel generator, which accounted for substantial fuel expenses (144,613 liters annually) and maintenance requirements. Energy production analysis showed solar PV as the primary contributor (79.3%), effectively supplemented by hydro (11.1%) and wind (1.95%) resources. The system's 545,886 kWh of surplus generation indicates robust capacity for meeting demand fluctuations. Environmental assessment recorded annual emissions of 378,542 kg CO_2 along with other pollutants, highlighting the need for further optimization to completely phase out fossil fuel dependence.

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