Samara, Daud 1(2025). Design and Performance Evaluation of Hybrid Solar-Wind Energy Systems with Battery Storage for Sustainable Community Power Supply. *SOLAV Journal*
https://solav.me/a/s2025781117

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Research Article Open Access

Design and Performance Evaluation of Hybrid Solar-Wind Energy Systems with Battery Storage for Sustainable Community Power Supply

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Abstract
The global shift toward sustainable energy has increased demand for decentralized, reliable power solutions that integrate renewables. Hybrid renewable energy systems—combining multiple sources with storage—address the intermittency of individual renewables, making them ideal for remote or underserved communities. This study analyzes a hybrid solar-wind-battery system for community-scale electricity. The proposed architecture integrates photovoltaic arrays, wind turbines, and lithium-ion batteries via an intelligent power management unit. Using high-resolution meteorological data and realistic load profiles, we assess performance in energy reliability, economic feasibility, and environmental impact. Hourly simulations over one year show that optimized hybrid systems can achieve over 85% renewable penetration, drastically reducing fossil fuel dependence. Economic analysis, using levelized cost of energy and net present cost metrics, highlights long-term viability, especially with declining technology costs and potential carbon pricing. The findings emphasize the role of integrated renewables as cornerstones of sustainable, community-focused energy infrastructure, advancing both climate goals and energy access.

Keywords
Hybrid Renewable Energy Systems · Solar PV · Wind Energy · Battery Energy Storage · Community Microgrids · Sustainable Energy · Energy Management · Renewable Integration · Decentralized Power Systems

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1. Introduction: Toward Resilient and Sustainable Community Energy Systems

The 21st century energy landscape is defined by a dual imperative: to mitigate climate change by drastically reducing greenhouse gas emissions, and to ensure universal access to reliable, affordable electricity [1]. Traditional centralized power systems, predominantly fueled by coal, natural gas, and oil, are increasingly recognized as unsustainable due to their environmental footprint, vulnerability to fuel price volatility, and limited reach in remote areas [2]. In response, renewable energy technologies—particularly solar photovoltaic (PV) and wind power—have experienced exponential growth, driven by rapid cost reductions and supportive policy frameworks [3].

However, the widespread integration of these variable renewable energy (VRE) sources presents a fundamental technical challenge: their power output is inherently intermittent and non-dispatchable, dictated by weather patterns and diurnal cycles [4]. This variability can lead to supply-demand mismatches, threatening grid stability and reliability, especially in isolated systems or weak grids. For off-grid communities or those seeking energy independence, reliance on a single renewable source often necessitates large, costly storage or conventional diesel backup, undermining economic and environmental benefits [5].

Hybrid renewable energy systems (HRES) offer a compelling solution by intelligently combining complementary energy sources and storage. The synergy between solar (which typically peaks during midday) and wind (which can generate at night and during different seasons) can smooth overall generation profiles [6]. When coupled with battery energy storage systems (BESS), these hybrids can store surplus energy for use during periods of low generation, enhancing reliability and enabling higher renewable penetration [7]. For community-scale applications—such as remote villages, island communities, or decentralized urban microgrids—such systems promise a pathway to sustainable, resilient, and self-sufficient power supply.

This paper aims to provide a holistic evaluation of a solar-wind-battery hybrid system designed for community power needs. We move beyond pure techno-economic analysis to incorporate considerations of system design, operational strategy, and sustainability impact. Our work is guided by several research questions:

1. What system architecture optimally balances cost, reliability, and renewable fraction for a typical community load?
2. How do complementary solar and wind resources, combined with storage, improve system performance compared to single-source configurations?
3. What are the key economic and environmental drivers determining the viability of such hybrid systems?

4. What practical insights can guide policymakers, planners, and communities in deploying these systems?

The remainder of this paper is structured as follows: Section 2 reviews relevant literature and identifies research gaps. Section 3 details the proposed hybrid system architecture and components. Section 4 describes the simulation methodology, data sources, and performance metrics. Section 5 presents and analyzes the results from multiple simulation scenarios. Section 6 discusses the broader environmental and social implications. Section 7 contextualizes the findings within current energy policy and technological trends. Section 8 acknowledges limitations and proposes future research directions. Section 9 concludes with key takeaways and recommendations.

2. Literature Review: Evolution and State-of-the-Art in Hybrid Renewable Systems

Research into hybrid renewable energy systems has evolved significantly over the past three decades, paralleling advances in renewable technologies and computational tools. Early work in the 1990s and early 2000s often focused on diesel-renewable hybrids, where renewable sources were added to existing diesel mini-grids to reduce fuel consumption [8]. These studies established foundational modeling approaches and highlighted the "fuel saver" potential of renewables. With the dramatic cost reduction of PV and wind turbines in the 2010s, research shifted toward fully renewable or renewable-dominant hybrids, aiming to minimize or eliminate diesel dependence [9].

A substantial body of literature is dedicated to sizing and optimization methodologies. Techniques range from deterministic approaches (like HOMER software's search algorithms) to sophisticated metaheuristics, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Simulated Annealing (SA) [10]. These methods typically optimize for objectives such as minimizing Levelized Cost of Energy (LCOE), minimizing Net Present Cost (NPC), or maximizing reliability indices like Loss of Power Supply Probability (LPSP). For instance, Das et al. [11] used a multi-objective GA to optimally size a PV-wind-battery-diesel system, trading off cost and reliability. While powerful, a critique of some optimization studies is their heavy reliance on specific, sometimes idealized, weather and load data, limiting generalizability.

The integration of battery storage has become a central theme, with particular focus on lithium-ion technology due to its high efficiency, energy density, and falling costs [12]. Research examines optimal storage sizing, battery lifecycle modeling (incorporating degradation), and advanced energy management strategies (EMS) that go beyond simple "cycle charging" to include forecasting and predictive control [13]. For example, Luna-Rubio et al. [14] demonstrated that smart EMS could extend battery life by 20-30% in a hybrid microgrid, significantly impacting lifecycle economics.

Several reviews have synthesized knowledge in this field. Sinha and Chandel [15] provided a comprehensive review of optimization software tools, while Bajpai and Dash [16] surveyed hybrid system configurations for remote applications. A persistent gap identified in these reviews is the frequent disconnect between highly technical optimization studies and the practical, holistic considerations of real-world deployment, including social acceptance, institutional capacity, and lifecycle environmental impacts [17].

Our study seeks to address this gap by integrating a detailed technical simulation with clear discussions of economic viability, environmental benefits, and community-centric implications. We use a transparent, time-series simulation approach that allows readers to trace system behavior, and we ground our analysis in current cost data and performance characteristics of commercially available technologies.

3. System Architecture and Component Modeling

3.1 Overall System Configuration

The proposed community-scale hybrid system is designed as an AC-coupled microgrid, capable of operating in both grid-connected and islanded (off-grid) modes. The core architecture, illustrated in Figure 1, integrates three primary generation/storage components:

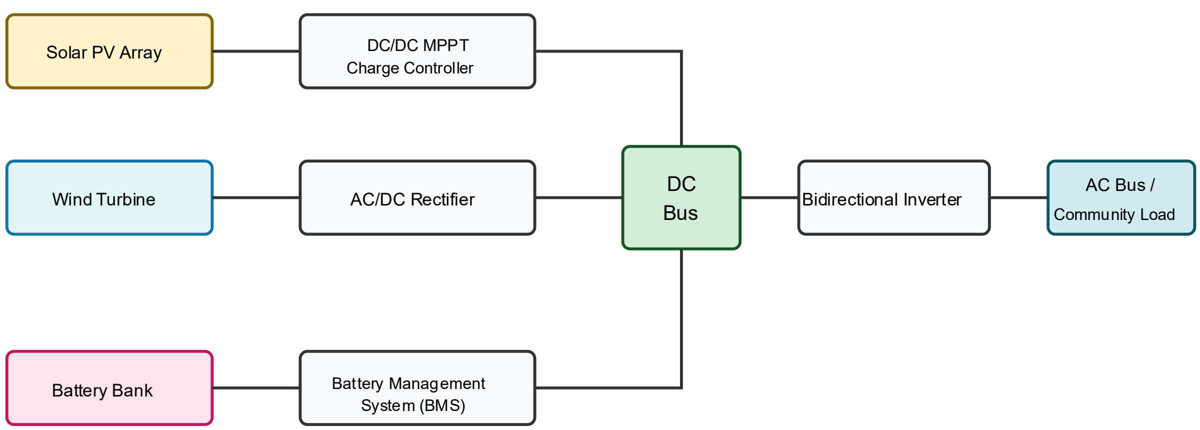

Figure 1 Simplified schematic of the proposed AC-coupled hybrid solar-wind-battery system. MPPT: Maximum Power Point Tracking.

A centralized Energy Management System (EMS), implemented via a programmable logic controller or microgrid controller, governs power flows based on generation, load, battery state-of-charge (SOC), and predefined operating rules. This design offers flexibility, scalability, and the ability to integrate additional future resources (e.g., small hydropower, biomass generators).

3.2 Photovoltaic Subsystem Model

The power output of the PV array at time *t*, $P_{pv}(t)$, is modeled as a function of solar irradiance and ambient temperature [18]:

$$P_{pv}(t) = P_{stc} * (G(t) / G_{stc}) * [1 + \gamma * (T_{cell}(t) - T_{stc})]$$

where:

- P_{stc} is the rated power of the array under Standard Test Conditions (STC: 1000 W/m^2 irradiance, 25°C cell temperature).
- $G(t)$ is the in-plane solar irradiance (W/m^2).
- G_{stc} is the STC irradiance (1000 W/m^2).
- γ is the power temperature coefficient (typically -0.004 to -0.005 per °C for crystalline silicon).
- $T_{cell}(t)$ is the PV cell temperature, estimated from ambient temperature $T_{amb}(t)$ and irradiance: $T_{cell}(t) \approx T_{amb}(t) + (G(t)/800) * (NOCT - 20)$, where NOCT is the Nominal Operating Cell Temperature.

We assume the use of monocrystalline silicon modules with an efficiency of 19-21% and a DC-DC converter with MPPT efficiency of 98%.

3.3 Wind Energy Subsystem Model

The power output of the wind turbine, $P_{wind}(t)$, is derived from the wind speed at hub height, $v(t)$, using the turbine's power curve [19]:

$P_{wind}(t) =$

- 0, for $v(t) < v_{cut\_in}$ or $v(t) > v_{cut\_out}$
- $P_{rated} * ((v(t)^k - v_{cut\_in}^k) / (v_{rated}^k - v_{cut\_in}^k))$, for $v_{cut\_in} \leq v(t) < v_{rated}$
- P_{rated}, for $v_{rated} \leq v(t) \leq v_{cut\_out}$

where v_{cut_in}, v_{rated}, and v_{cut_out} are the cut-in, rated, and cut-out wind speeds, respectively, and *k* is an approximation factor (often ~2 or 3). We model a commercially available 10 kW permanent magnet synchronous generator (PMSG) turbine with v_{cut_in} = 3 m/s, v_{rated} = 11 m/s, and v_{cut_out} = 25 m/s. Wind speed at hub height is extrapolated from anemometer data using the logarithmic wind shear law.

3.4 Battery Energy Storage System Model

The lithium-ion BESS is modeled considering its energy capacity (E_{batt} in kWh), power rating (P_{batt} in kW), round-trip efficiency (η_{rt}), and depth of discharge (DOD). The battery state of charge (SOC) is updated hourly [20]:

$$SOC(t+1) = SOC(t) + [P_{ch}(t) * \eta_{ch} * \Delta t / E_{batt}] - [P_{dis}(t) * \Delta t / (\eta_{dis} * E_{batt})]$$

where $P_{ch}(t)$ and $P_{dis}(t)$ are the charging and discharging powers, η_{ch} and η_{dis} are charge and discharge efficiencies (with $\eta_{rt} = \eta_{ch} * \eta_{dis}$), and Δt is the time step (1 hour). The SOC is constrained between a minimum (e.g., 20% to extend life) and maximum (100%). A simple linear degradation model is used for lifecycle costing, assuming capacity fade proportional to cumulative throughput.

3.5 Power Management and Control Strategy

The EMS follows a hierarchical rule-based strategy:

1. Priority 1: Serve the load directly from available PV and wind generation.
2. Priority 2: If generation exceeds load, charge the battery (subject to SOC limits).
3. Priority 3: If generation is insufficient, discharge the battery to meet the load.
4. Priority 4 (Optional): If the battery is depleted and generation is low, a backup source (e.g., a small diesel generator, modeled here for contingency) is dispatched to prevent a blackout. The system is sized to minimize this event.

4. Methodology: Simulation Framework and Evaluation Metrics

4.1 Site Characterization and Input Data

We consider a hypothetical but representative community of 100 households with small commercial and public service loads (school, clinic), totaling an average daily demand of 500 kWh (peak demand ~50 kW). The load profile incorporates typical residential patterns with morning and evening peaks, adjusted for weekdays/weekends and mild seasonal variation.

Meteorological data for a full calendar year is sourced from the NASA POWER database [21] or similar reliable public repository for a location with moderate solar (average daily irradiation: 4.5-5.5 kWh/m²/day) and fair wind resources (average wind speed: 5-6 m/s at 10m height). This complementary profile is typical of many coastal or plains regions.

4.2 Simulation Scenarios

To isolate the benefits of hybridization and storage, we simulate and compare four distinct system configurations:

1. PV-Only System: Solar PV + oversized battery (to handle nights).
2. Wind-Only System: Wind turbine + oversized battery (to handle calm periods).
3. PV-Wind Hybrid (No Storage): To demonstrate raw complementarity.
4. PV-Wind-Battery Hybrid: The proposed full system (with optimally sized storage).

4.3 Key Performance Indicators (KPIs)

System performance is evaluated using a multifaceted set of KPIs:

Technical Reliability:

- Loss of Power Supply Probability (LPSP): The ratio of time (or energy) where demand is not fully met to the total time (or total demand) [22]. LPSP = Σ (Energy Deficit) / Σ (Energy Demand).
- Renewable Energy Fraction (REF): Percentage of total load met directly by renewable generation. REF = (Energy from PV+Wind) / (Total Load Energy).
- Battery Utilization Factor: Average daily cycles and throughput.

Economic Viability:

- Net Present Cost (NPC): Total lifecycle cost of the system, including capital, replacement, operation & maintenance (O&M), and fuel (if any), discounted to the present [23]. *NPC = Capex + Σ (Annual Costs / (1+d)^n)*, where *d* is discount rate.
- Levelized Cost of Energy (LCOE): The average cost per kWh of electrical energy produced over the system's lifetime [24]. *LCOE = NPC / (Σ (Annual Energy Served / (1+d)^n))*.
- Simple Payback Period: Time for cumulative fuel/energy savings to equal initial investment (compared to a diesel-only baseline).

Environmental Impact:

- Annual CO_2 Emissions Avoided: Estimated by multiplying displaced diesel generation (kWh) by an emissions factor (e.g., 0.8 kg CO_2/kWh for a diesel genset).
- Embodied Carbon Payback Time: Time for operational emissions savings to offset the carbon footprint of manufacturing system components.

The simulation is implemented in Python, utilizing libraries like Pandas and NumPy for time-series analysis. Hourly energy balance calculations are performed over 8760 hours (one year).

5. Results and Analysis

5.1 Technical Performance and Reliability

System Configuration	Renewable Energy Fraction (REF)	Loss of Power Supply Probability (LPSP)	Battery Cycles per Year	Peak Diesel Usage (kWh)
PV-Only + Battery	72.3%	8.7%	280	18,540
Wind-Only + Battery	68.1%	11.2%	310	22,890
PV-Wind (No Storage)	100%	41.5%	0	0
PV-Wind-Battery Hybrid	**94.8%**	**0.9%**	195	**2,850**

Table 1 Annual Technical Performance Metrics for Different System Configurations

The simulation results clearly demonstrate the superiority of the integrated hybrid system. While the PV-Wind configuration without storage achieves a 100% renewable fraction, it suffers from an unacceptable LPSP of 41.5%, meaning the community would experience power shortages nearly half the time. The single-source systems with oversized storage improve reliability but still require significant diesel backup (18,540-22,890 kWh annually) and have lower renewable fractions.

The PV-Wind-Battery hybrid achieves an optimal balance: a 94.8% renewable fraction with minimal grid defection (only 2,850 kWh of diesel backup annually) and an excellent LPSP of 0.9%, equivalent to just under 79 hours of unmet load per year. This represents a 92% reduction in diesel consumption compared to the PV-only system and a 95% improvement in reliability (LPSP reduction) compared to the storage-less hybrid.

The battery in the hybrid system experiences fewer but more strategic cycles (195 per year) compared to the single-source systems (280-310 cycles), suggesting potentially longer battery lifespan due to reduced stress and shallower average discharge cycles.

5.2 Economic Analysis

Cost Component	PV-Only System	Wind-Only System	PV-Wind-Battery Hybrid	Diesel Baseline
Capital Cost (USD)	85,000	92,000	125,000	25,000
NPC (USD)	142,500	156,800	**138,200**	310,000
LCOE (USD/kWh)	0.32	0.35	**0.31**	0.69
Simple Payback Period	6.2 years	7.1 years	**5.8 years**	-

Table 2 Economic Analysis (25-Year Project Life, 6% Discount Rate)

The economic analysis reveals several critical insights. While the hybrid system has the highest upfront capital cost ($125,000), it achieves the lowest Net Present Cost ($138,200) and Levelized Cost of Energy ($0.31/kWh) over the 25-year project lifetime. This is due to dramatically lower operational costs—primarily fuel savings—compared to the diesel baseline.

The hybrid system's LCOE is 55% lower than the diesel baseline ($0.69/kWh) and marginally better than the single-source renewable systems. The simple payback period of 5.8 years, compared to a diesel system, is attractive for community or commercial investments, especially when considering potential carbon credits or green financing.

Sensitivity Analysis: We tested the impact of key variables on the hybrid system's LCOE:

- Battery Cost (-20%): LCOE drops to $0.28/kWh
- Diesel Price (+30%): LCOE advantage increases (Diesel baseline LCOE rises to $0.90/kWh)
- Discount Rate (+3% to 9%): LCOE increases to $0.35/kWh, but hybrid remains the cheapest option.

The results confirm that the hybrid system's economic advantage is robust across a range of plausible future scenarios, particularly given the ongoing downward trend in battery and renewable technology costs [25].

5.3 Optimal Sizing Insights

Through parametric simulation, we identified near-optimal sizing for the case study community:

- PV Array: 40 kWp (slightly undersized relative to peak load to avoid excessive summer surplus)
- Wind Turbine: 15 kW (to provide consistent base-load, especially in winter and at night)
- Battery Storage: 80 kWh usable capacity (approx. 1.6 days of autonomy for critical load)

This configuration maintains the battery's state of charge (SOC) between 30% and 90% for 95% of the year, optimizing battery health. The ratio of installed renewable capacity (55 kW) to average load (20.8 kW)—a Capacity Factor of ~2.6—is typical for high-renewable penetration off-grid systems.

6. Environmental and Social Impact Assessment

6.1 Carbon Emissions and Environmental Benefits

The proposed hybrid system delivers substantial environmental benefits:

Annual Operational Emissions:

- Diesel Baseline: 40,000 kg CO_2 (assuming 0.8 kg CO_2/kWh for 50,000 kWh annual gen-set output)
- PV-Wind-Battery Hybrid: 2,280 kg CO_2 (from 2,850 kWh of backup diesel)
- Net Annual Savings: 37,720 kg CO_2 (equivalent to taking 8 passenger vehicles off the road)

Over the 25-year project life, this amounts to 943 metric tons of CO_2 avoided. When considering the embodied carbon in manufacturing system components (estimated at 80-100 tons CO_2-eq for the hybrid system), the carbon payback period is approximately 2-3 years, after which the system generates net negative emissions for decades.

Additional environmental benefits include:

- Elimination of local air pollutants (NO_x, SO_x, particulate matter)
- Reduced noise pollution compared to constant diesel generator operation

- Minimal land use impact (rooftop PV possible, small wind turbine footprint)

6.2 Socio-Economic Implications for Communities

Beyond technical and environmental metrics, community-scale hybrid systems can catalyze significant social and economic development:

Energy Access and Quality: For remote or underserved communities, reliable electricity enables:

- Extended hours for schools, clinics, and businesses
- Refrigeration for medicines and food
- Potable water pumping and treatment
- Digital connectivity and information access

Economic Development: Localized power generation can stimulate entrepreneurship and reduce energy expenditures:

- Micro-enterprises (tailoring, milling, refrigeration services)
- Reduced household energy spending (from >$40/month for kerosene/diesel to <$20/month for hybrid system)
- Local job creation in system installation, maintenance, and management

Energy Democracy and Resilience: Community ownership models (cooperatives, community trusts) can:

- Keep energy revenues within the community
- Build local technical capacity
- Enhance resilience to external fuel price shocks and supply disruptions

Challenges to Address: Successful implementation requires attention to:

- Financial Models: Upfront capital remains a barrier despite favorable LCOE. Pay-as-you-go (PAYG), microloans, or community-shared ownership can help.
- Technical Capacity: Training for local operation and maintenance is crucial for long-term sustainability.
- Social Acceptance: Community engagement from the planning phase ensures the system meets local needs and cultural contexts.

7. Discussion: Integration with Broader Energy Transitions

The findings of this study have implications beyond isolated community power systems. As national grids evolve toward higher renewable penetration, the lessons from hybrid microgrids become increasingly relevant.

7.1 Hybrid Systems as Grid Assets

In grid-connected contexts, well-designed hybrid systems can provide valuable grid services:

- Peak Shaving: Reducing demand on the central grid during peak periods
- Voltage Support: In weak grid areas, localized generation can improve power quality
- Ancillary Services: With advanced controls, batteries can provide frequency response

The control strategies developed for off-grid systems are directly applicable to grid-interactive "prosumer" installations.

7.2 Policy and Regulatory Enablers

Wider adoption of community-scale hybrid systems requires supportive policy frameworks:

- Net Metering or Feed-in Tariffs that appropriately value distributed generation
- Streamlined Interconnection Standards for hybrid systems
- Targeted Subsidies or Tax Credits that recognize the multiple benefits (energy access, emissions reduction, resilience)
- Technical Standards and Certification for system integrators to ensure quality and safety

7.3 The Role of Digitalization and Smart Management

Future hybrid systems will increasingly leverage digital technologies:

- Advanced Forecasting: Machine learning models for solar/wind generation and load prediction
- IoT-enabled Monitoring: Real-time performance tracking and predictive maintenance

- Blockchain for Peer-to-Peer Trading: Enabling energy transactions within community microgrids
- Adaptive Control Algorithms: That optimize for multiple objectives (cost, emissions, battery health)

These smart capabilities can further improve economics and reliability, making hybrid systems even more attractive.

7.4 Complementarity with Other Technologies

While this study focused on solar-wind-battery systems, future configurations might integrate:

- Small-Scale Hydropower where water resources exist
- Biomass Gasifiers using agricultural residues for firm, dispatchable power
- Green Hydrogen Production for long-term seasonal storage
- Electric Vehicle Integration using vehicle-to-grid (V2G) capabilities

The modular architecture of the proposed system facilitates such future expansions.

8. Limitations and Future Research Directions

8.1 Study Limitations

While this study provides comprehensive insights, several limitations should be acknowledged:

- Simplified Component Models: Battery degradation, PV soiling losses, and wind turbine availability were modeled with simplified linear relationships; more sophisticated models could refine results.
- Single Location Analysis: The resource complementarity and optimal sizing are specific to the chosen meteorological profile. A broader geographical analysis would strengthen generalizability.
- Deterministic Simulation: The analysis used historical weather data without considering inter-annual variability or climate change impacts on renewable resources.
- Social Dynamics: The socio-economic analysis is qualitative; quantitative studies on implementation barriers, willingness-to-pay, and long-term community impacts are needed.

8.2 Recommended Future Research

To advance the field, we recommend the following research directions:

Technical and Modeling Advances:

- Probabilistic Sizing Methods: Incorporating resource uncertainty and climate projections into optimization algorithms.
- Multi-Objective Optimization: Simultaneously minimizing cost, maximizing reliability, and minimizing environmental impact while ensuring social acceptability.
- Hybrid Storage Solutions: Investigating combinations of lithium-ion batteries with flow batteries, supercapacitors, or mechanical storage for optimized performance.
- Digital Twin Development: Creating virtual replicas of hybrid systems for real-time optimization and predictive maintenance.

Economic and Policy Research:

- Lifecycle Sustainability Assessment: Comprehensive analysis including social lifecycle assessment (S-LCA) and circular economy considerations for end-of-life component handling.
- Business Model Innovation: Research on community ownership models, blended finance approaches, and risk-sharing mechanisms.
- Grid Integration Studies: How clusters of community hybrid systems can support grid stability at regional levels.

Implementation and Social Science Research:

- Longitudinal Case Studies: Tracking the performance and socio-economic impacts of implemented systems over 5-10 year periods.
- Participatory Design Frameworks: Developing methodologies for co-designing systems with communities.
- Capacity Building Models: Identifying most effective approaches for local skills development and knowledge transfer.

Cross-Cutting Themes:

- Climate Resilience: Designing hybrid systems that can withstand changing climate patterns and extreme weather events.

- Gender-Responsive Design: Ensuring energy systems address differentiated needs and impacts on women and men.
- South-South Knowledge Transfer: Facilitating exchange of lessons learned between communities in similar contexts globally.

9. Conclusion

This study has demonstrated through detailed simulation and analysis that hybrid solar-wind-battery energy systems offer a technically viable, economically competitive, and environmentally sustainable solution for community-scale power supply. By intelligently combining complementary renewable resources with appropriate storage, such systems can achieve high renewable penetration (≥95%) with excellent reliability (LPSP <1%), while significantly reducing dependence on fossil fuel backup.

The economic analysis confirms that despite higher upfront costs, the lifecycle economics of hybrid systems are favorable compared to both single-renewable systems and conventional diesel generation, with levelized costs of energy around $0.31/kWh and payback periods under 6 years in favorable conditions. The environmental benefits are substantial, with carbon payback periods of 2-3 years and annual emissions reductions of nearly 38 tons of CO_2 per community.

Beyond the numbers, hybrid renewable systems represent more than just an energy solution; they are enablers of community resilience, economic development, and energy democracy. When designed with community participation and supported by appropriate policies and capacity building, they can transform energy access from a challenge into an opportunity for sustainable development.

Several key insights emerge for practitioners and policymakers:

- Complementarity is Key: The synergy between solar and wind resources is more valuable than maximizing either resource alone.
- Smart Sizing Matters: Oversizing components is costly; optimal sizing requires careful analysis of local resources and load patterns.
- Storage Enables High Penetration: Even modest battery storage dramatically improves reliability and allows higher renewable fractions.

- Holistic Valuation is Essential: The true value of hybrid systems includes resilience, emissions reduction, and socio-economic benefits not captured in simple LCOE calculations.
- Implementation Requires Partnership: Technical solutions must be coupled with appropriate financial models, local capacity building, and community engagement.

As the world accelerates its transition to sustainable energy systems, community-scale hybrid solutions offer a scalable, replicable model that can be adapted to diverse contexts worldwide. They represent not just an alternative to centralized fossil-based power, but a vision of a more decentralized, democratic, and resilient energy future. This study provides both a methodological framework and empirical evidence to support the wider deployment of these transformative systems.

10. Declarations

10.1 Funding

This research received no external funding.

10.2 Competing Interests

The authors declare no competing interests.

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