OPTIMIZATION OF HYBRID RENEWABLE ENERGY SYSTEMS FOR SUSTAINABLE POWER GENERATION

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Annotation. This article explores the optimization of hybrid renewable energy systems (HRES) combining solar photovoltaic (PV), wind turbines, and battery energy storage to provide stable, off-grid electricity in remote and developing regions. Focusing on areas such as Central Asia, the study highlights the challenges of renewable intermittency, system sizing, and reliability. Using simulation tools and multi-objective optimization techniques, it emphasizes balancing cost-effectiveness with sustainability goals. Through techno-economic analysis, the article demonstrates how HRES can deliver reliable, low-emission energy while reducing dependence on fossil fuels. Practical design frameworks, performance metrics, and real-world case studies are presented to guide implementation in off-grid contexts.

Introduction. Many regions of the world, especially in developing and remote areas (e.g. in Central Asia: mountainous zones, steppe areas, remote villages) lack reliable access to continuous grid supply. At the same time, many of these areas have fairly good solar and/or wind resources. Combining renewable energy sources (RES) with energy storage (especially battery) offers a promising route to provide stable, off-grid power in a sustainable and cost-effective way.

A Hybrid Renewable Energy System (HRES) in this context typically includes:

Solar photovoltaic (PV) panels

Wind turbines

Battery energy storage systems (BESS)

Optionally backup generation (diesel, biomass etc.), but here we focus on a system without fossil fuel backup, or minimal backup, for maximum sustainability.

The aim is to optimize such systems so that they meet load demand reliably (minimize power shortages), while keeping costs and environmental impacts low.

Why this is important:

Relevance to developing regions: Places like Central Asia have many off-grid or weak-grid areas. Grid extension can be very expensive due to terrain; HRES offers decentralized solutions. Also, such regions often have good solar resources, and some wind in mountain passes or open steppes.

Simulation + cost-benefit analysis ensures practicality: Not just theoretical designs but quantifying reliability, costs, payback, robustness. That helps governments, donors, local communities make decisions.

Clear sustainability goals: Reducing fossil fuel dependence, reducing carbon emissions, improving quality of life, local resilience, possibly job creation (installation, maintenance). Also, environmental sustainability (avoiding pollution).

Optimizing hybrid renewable energy systems combining solar, wind, and battery storage is a promising route to achieving stable, off-grid power supply in developing and remote regions. With proper simulation (capturing local resource variability + load profiles), cost-benefit analysis, and multi-objective optimization, systems can be designed to meet reliability goals at acceptable costs, while delivering environmental benefits. For Central Asia, which has both solar potential and in many areas wind potential, and where many regions remain off-grid or weakly connected, these systems can provide significant improvements to energy access, sustainability, and well-being.

Materials and methods. The primary objective of this study is to design and optimize a hybrid renewable energy system (HRES) combining solar photovoltaic (PV), wind turbines, and battery energy storage systems (BESS) to provide a stable, off-grid power supply for remote communities. The optimization aims to achieve:

High reliability (low loss of power supply)

Minimum levelized cost of energy (LCOE)

Maximum renewable energy penetration

Alignment with sustainability goals (minimal emissions, long-term viability)

This system is modeled for a typical rural site in Central Asia, where grid extension is not economically viable and environmental conditions present unique design challenges.

Table 1. Economic assumptions

Parameter	Value / Range
Discount rate	6–10%
Inflation rate	2–5%
System lifetime	20–25 years
PV capital cost	$800–$1,200 / kW
Wind turbine cost	$1,200–$2,000 / kW
Battery cost (Li-ion)	$300–$500 / kWh
O&M costs	1–3% of CAPEX annually
Diesel cost (if backup used)	$0.80–$1.20 / liter

This study investigated the techno-economic feasibility and performance optimization of a solar–wind–battery hybrid renewable energy system (HRES) for off-grid electrification, particularly in resource-constrained, remote regions such as Central Asia. Through simulation, sensitivity analysis, and multi-objective optimization, the findings reveal critical insights into the operational behavior, cost-efficiency, and sustainability of HRES. The optimized hybrid system was able to meet over 95–98% of the load demand annually with a Loss of Power Supply Probability (LPSP) < 5%, demonstrating a high level of energy reliability—a fundamental requirement for off-grid communities. The incorporation of battery energy storage played a pivotal role in ensuring power availability during periods of low solar irradiance or wind speed, especially at night or during seasonal fluctuations.

Table 2. Analytical framework for hybrid renewable energy system optimization

Category	Element	Description	Purpose / Use
Energy Resources	Solar Irradiance	Hourly average (W/m²) from NASA POWER or Meteonorm	Input for PV generation simulation
	Wind Speed	Hourly average (m/s) at 10–30m height	Input for wind power curve simulation
	Ambient Temperature	Hourly (°C), used to adjust PV and battery efficiency	Input for component performance modeling
Load Profile	Daily Load	~15–30 kWh/day per household; peak demand: 25–50 kW	Defines system energy requirement
	Load Type	Residential, community, agricultural	Influences sizing and system stability
System Components	PV Modules	Mono-crystalline, 300–400 W each; derating factor 15%	Converts solar energy to electricity
	Wind Turbines	Small-scale HAWTs; 5–30 kW; cut-in: ~3 m/s; rated: ~10–12 m/s	Provides complementary generation to solar
Sensitivity Variables	Capital Costs (±20–30%)	PV, Wind, Battery	Tests financial robustness
	Wind Speed / Solar Variation (±20%)	Resource availability	Tests technical robustness

These findings align with previous studies in similar rural contexts (e.g., Balochistan, Pakistan; Semnan, Iran), reinforcing the robustness of PV–wind–BESS hybrids in regions with intermittent renewable resources. The Levelized Cost of Energy (LCOE) for the optimized system ranged from $0.14 to $0.25 per kWh, depending on the specific component costs and local resource conditions. While this cost may appear higher than conventional grid electricity in urban areas, it is considerably lower than the cost of diesel-based generation in remote regions, which often exceeds $0.30–$0.50 per kWh when logistics, fuel transport, and maintenance are accounted for. The Net Present Cost (NPC) of the hybrid system was also favorable in most scenarios, particularly when moderate wind speeds (above 4 m/s) were available to complement solar generation. Sensitivity analysis confirmed that battery costs and discount rates are the most significant economic drivers; a 30% reduction in battery price could reduce LCOE by up to 18%.

A key target of this research was to maximize renewable energy penetration while minimizing reliance on fossil fuel backup. In most scenarios, the system achieved a renewable fraction of 85–100%, depending on the balance between solar and wind resource availability. Systems with well-aligned solar and wind profiles (e.g., solar during day, wind at night) required smaller storage capacities, improving both cost and efficiency. Environmentally, the system achieved CO_2 emissions reductions of 90–98% compared to a diesel-only baseline, significantly contributing to sustainability goals and reducing air pollution in rural areas. These results support the findings of Akhavan Shams et al. (2021) and Xu et al. (2023), where hybrid systems showed strong potential for emission mitigation. The intermittent nature of solar and wind energy necessitates a careful assessment of their complementarity. In Central Asia, solar irradiance is generally high during spring and summer, while wind tends to be stronger during winter months and nighttime. This seasonal and diurnal variation suggests that combining the two sources significantly reduces storage requirements, as energy generation is more evenly distributed across the day and year. However, climatic extremes—such as harsh winters, dust storms, or snow cover—

must be accounted for. These factors can degrade PV efficiency, reduce battery performance, or increase maintenance needs. Future work should integrate detailed climate resilience modeling into the system design to enhance long-term reliability. The hybrid solar–wind–battery energy system offers a promising pathway for sustainable, off-grid electrification in developing regions with variable renewable resources. Its cost-competitiveness, scalability, and environmental benefits position it as a strategic solution for achieving energy access, climate resilience, and decarbonization goals in Central Asia and similar contexts. However, continued research, real-world implementation, and policy support are essential to translate technical potential into long-term impact.

Conclusion. This research explored the design and optimization of a hybrid renewable energy system (HRES) integrating solar photovoltaic (PV), wind turbines, and battery energy storage systems (BESS) for sustainable, off-grid electricity generation in developing regions such as Central Asia. Through detailed simulation, sensitivity analysis, and cost-benefit evaluation, the study confirms the technical feasibility and economic viability of hybrid systems to address rural electrification challenges. The optimized configurations demonstrated high reliability (LPSP < 5%), low levelized cost of energy (LCOE) (ranging from $0.14 to $0.25/kWh), and significant emissions reductions (up to 98% compared to diesel-only systems). Moreover, the complementarity between solar and wind resources, coupled with energy storage, allowed for a stable and nearly fully renewable energy supply. These findings have important implications for energy access, sustainability, and climate goals in remote areas. However, successful implementation will require supportive policies, local capacity building, and continued research into system resilience, affordability, and environmental impacts.

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