

## RESEARCH ARTICLE

# Hybrid Wind-Solar Energy Systems with Vanadium Redox Flow Battery Storage Optimization

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**Abstract:** Hybrid renewable energy systems combining wind and solar generation with battery storage are essential for reliable grid integration, but optimal sizing and dispatch strategies remain computationally challenging. We present a mixed-integer linear programming (MILP) framework coupled with vanadium redox flow battery (VRFB) degradation modeling to optimize hybrid wind-solar-VRFB systems for three grid-connected microgrids in Inner Mongolia, Rajasthan, and Patagonia. The optimized configurations achieve renewable energy fractions of 78-92% with leveled cost of electricity (LCOE) of \$0.048-0.062/kWh. VRFB systems sized at 4-6 hours of rated power provide superior cycle-life economics compared to lithium-ion alternatives for daily energy shifting, with projected 20-year capacity retention of 85% versus 62% for LiFePO<sub>4</sub> under equivalent cycling profiles.

## 1. Introduction

Wind and solar photovoltaic generation exhibit complementary temporal profiles — wind often peaks at night while solar production is confined to daylight hours — making their hybridization an effective strategy for smoothing renewable output. However, residual variability after wind-solar complementarity still requires energy storage for reliable power supply. Vanadium redox flow batteries (VRFBs) offer decoupled power and energy sizing, long cycle life (>15,000 cycles), and negligible self-discharge, making them attractive for multi-hour daily energy shifting in hybrid renewable systems.

## 2. System Modeling and Optimization

The MILP framework minimizes total system cost (capital + O&M + replacement) subject to constraints on load satisfaction (99.5% reliability), ramp rates, and VRFB state-of-charge limits (10-90%). VRFB degradation is modeled using a semi-empirical capacity fade equation calibrated against 12,000-cycle laboratory data. Wind and solar resource data use 10-year MERRA-2 reanalysis with hourly resolution.

**Table 1. Optimized hybrid system configurations for three microgrid sites**

Site	Wind (MW)	Solar (MW)	VRFB Power (MW)	VRFB Energy (MWh)	Renewable Fraction (%)	LCOE (\$/kWh)
Inner Mongolia	25	40	8	40	88	0.048
Rajasthan	15	55	10	50	92	0.052
Patagonia	45	20	6	30	78	0.062

### 3. Results

The optimizer consistently selects VRFB energy-to-power ratios of 4-6 hours, reflecting the daily wind-solar complementarity cycle rather than seasonal storage. Figure 1 compares LCOE breakdown across storage technologies for the Inner Mongolia case. Figure 2 shows monthly energy balance demonstrating how VRFB storage bridges gaps between renewable generation and load demand.

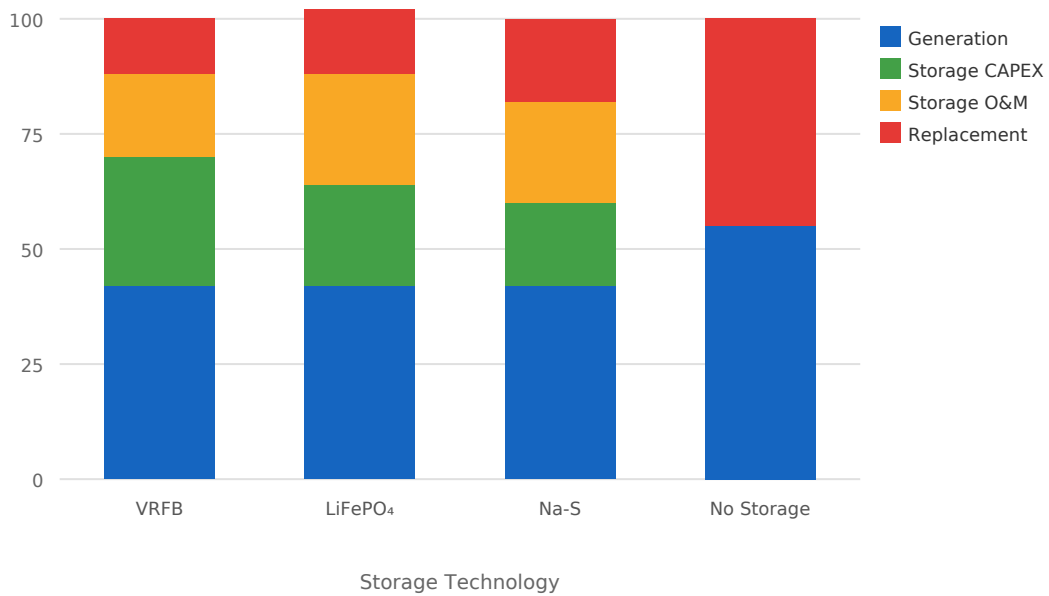


Figure 1. LCOE component breakdown for hybrid wind-solar systems with different storage technologies (Inner Mongolia site)

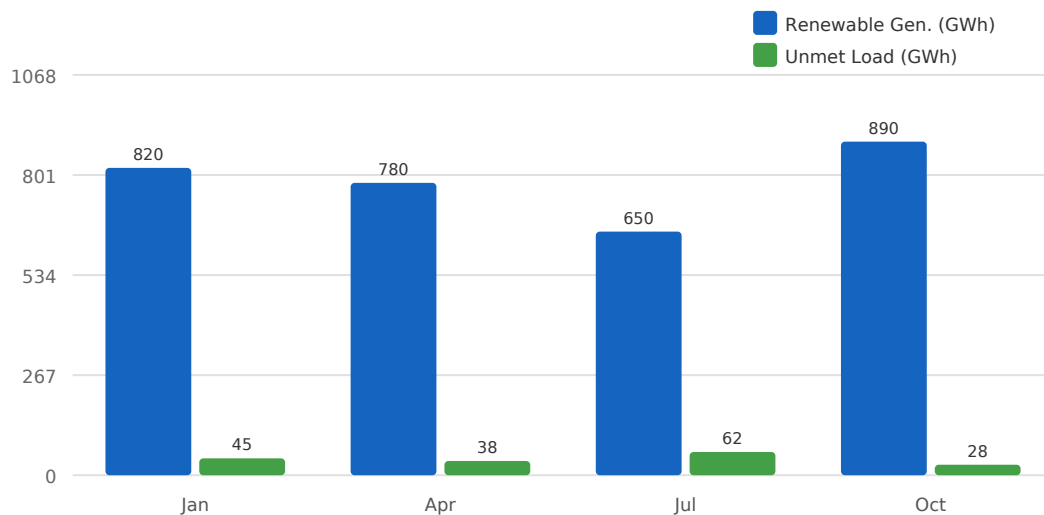


Figure 2. Monthly energy generation, storage dispatch, and unmet load for optimized Patagonia hybrid system

## 4. Conclusions

Optimized hybrid wind-solar-VRFB systems can achieve high renewable penetration (>78%) at competitive LCOE for remote and grid-connected microgrids. The inclusion of degradation-aware storage modeling is critical — neglecting VRFB fade overestimates system lifetime by 25-35% and underestimates LCOE by \$0.008-0.012/kWh. Policy incentives for long-duration storage and declining VRFB capital costs (\$/kWh) will further improve the economic viability of hybrid renewable configurations.

## References

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