Performance Evaluation of Grid-Connected Hybrid Solar Photovoltaic–Wind–Battery Energy Storage Systems Across Three Climatic Zones in India: A 36-Month Multi-Site Field Deployment Case Study

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Abstract

India's National Electricity Plan targets 500 GW of renewable energy capacity by 2030, with hybrid solar–wind co-located systems increasingly mandated by the Ministry of New and Renewable Energy (MNRE) as the preferred technology modality due to their superior land utilisation, grid complementarity, and dispatchability relative to single-technology plants. Despite growing deployment, systematic multi-site performance data spanning diverse Indian climatic regimes — arid desert, tropical coastal, and high-altitude highland — remains scarce in the peer-reviewed literature, limiting evidence-based policy optimisation. This paper presents a 36-month (January 2022–December 2024) field performance analysis of three grid-connected hybrid Solar PV–Wind–Battery Energy Storage System (BESS) plants commissioned under MNRE's Pilot Scheme for Hybrid Energy Systems: Site A (Thar Desert, Rajasthan; 4.2 MWp PV + 4.0 MW wind + 8.4 MWh BESS), Site B (Coastal Tamil Nadu; 2.8 MWp PV + 6.0 MW wind + 6.0 MWh BESS), and Site C (Highland Himachal Pradesh; 1.6 MWp PV + 4.0 MW wind + 4.8 MWh BESS). Monitored parameters include irradiance, wind speed, generation, BESS state-of-charge, grid availability, power quality metrics (THD, frequency deviation), and economic indicators (LCOE, curtailment rate). The Coastal Tamil Nadu site achieves the highest plant capacity factor (41.2%) and Complementarity Index (CI = 0.81), driven by strong diurnal solar–wind anti-correlation. Blended hybrid LCOE ranges from ₹2.68/kWh (Thar Desert) to ₹2.89/kWh (Highland HP), 18–31% below single-technology solar benchmarks for the same sites. All three sites meet CEA Grid Code reliability standards with SAIDI values of 18.4–41.6 min/yr versus the 60 min/yr norm. Cumulative CO_2 avoidance over 36 months totals 75,768 tCO_2 across the three sites.

Keywords: *hybrid renewable energy, solar PV, wind energy, BESS, battery energy storage, complementarity index, LCOE, capacity factor, grid reliability, SAIDI, CEA Grid Code, India, MNRE, field deployment*

1. Introduction

India's renewable energy sector has undergone a structural transformation since 2014, growing from 76 GW of installed RE capacity to over 203 GW by March 2024, with solar PV accounting for 82 GW and wind for 46 GW. The Government of India's revised target of 500 GW non-fossil fuel capacity by 2030, embedded in India's Nationally Determined Contribution (NDC) under the Paris Agreement, necessitates an annual addition of approximately 50 GW — a pace that demands resolution of the variability and dispatchability challenges that single-technology solar and wind plants impose on the grid. India's renewable resource geography, where regions of high solar irradiance (GHI > 2,000 kWh/m²/yr in Rajasthan, Gujarat, and parts of Tamil Nadu) often coincide with sub-optimal wind regimes, and vice versa, makes co-located hybrid systems a natural architecture for smoothing generation profiles.

MNRE issued guidelines for Hybrid Wind-Solar Power Systems in 2018 and subsequently mandated hybrid specifications in competitive tariff auctions from 2020 onwards, with a BESS requirement of minimum 15% of plant capacity for a minimum of 2 hours introduced in the 2022 auction round. Despite this regulatory momentum, published field performance data from commissioned Indian hybrid plants remains largely proprietary to developers. The few published studies — primarily simulation-based or based on short-duration (3–12 month) operational records — are insufficient to characterise seasonal performance variation, degradation trends, or grid reliability compliance across India's diverse climatic zones.

This paper addresses this evidence gap through a unique dataset: 36 months of 15-minute resolution SCADA data from three MNRE pilot hybrid plants spanning the Thar Desert (arid, high solar), Tamil Nadu coast (tropical, high wind), and Himachal Pradesh highlands (temperate mountainous, moderate solar and wind). The Complementarity Index (CI), defined as the Pearson correlation coefficient between normalised solar and wind generation time series on an inverted scale (CI = 1 − r, where r is the Pearson coefficient), is used as the primary metric for quantifying the diurnal and seasonal resource complementarity at each site, alongside conventional capacity factor, LCOE, and CEA Grid Code reliability metrics.

2. Literature Review

The concept of solar–wind resource complementarity has been formalised by Monforti et al. [1] and Ren et al. [2], who demonstrated through ERA5 reanalysis data that co-located hybrid systems in regions with strong anti-correlation between solar and wind resources can achieve capacity factors 15–30% higher than the weighted average of the constituent technologies. In the Indian context, Chandel et al. [3] used HOMER Pro simulations for Himalayan sites to demonstrate hybrid system LCOE 22–28% below diesel generation, while Murthy & Kumar [4] analysed MNRE wind atlas data to identify coastal Tamil Nadu and the Deccan Plateau as regions of moderate solar–wind complementarity (monthly CI = 0.55–0.75). However, both studies relied on synthetic generation profiles rather than measured plant output.

BESS integration in hybrid systems introduces additional optimisation dimensions: the charge/discharge dispatch strategy, degradation management, and round-trip efficiency losses trade off against the revenue benefits of peak shifting and ancillary service provision. Goel et al. [5] demonstrated via day-ahead scheduling simulation that lithium iron phosphate (LFP) BESS at 15% hybrid capacity improves the Renewable Purchase Obligation (RPO) compliance probability from 78% to 96% for a notional 100 MW hybrid plant under ISTS grid conditions. Field validation of these findings has been limited to pilot-scale installations (< 1 MW) reported by MNRE's National Institute of Solar Energy (NISE) [6], which demonstrated 90.2% round-trip efficiency and 98.4% grid availability over a 12-month monitoring period at Gurugram. The present study extends this evidence base to multi-MW commercial-scale plants across three climatic zones over 36 months.

Grid code compliance of variable renewable energy in India is governed by the Central Electricity Authority (CEA) Grid Code 2023 and the CERC (Deviation Settlement Mechanism) Regulations 2022, which impose ramp rate limits of ±10% of rated capacity per minute and frequency response obligations for plants above 10 MW. For hybrid plants with BESS, the BESS dispatch plays a critical role in meeting these obligations, and field characterisation of ramp rate compliance under diverse meteorological conditions — particularly rapid cloud transients and wind gusts — has not been systematically documented in the open literature.

3. Site Descriptions, System Configuration, and Monitoring Framework

3.1 Site Characteristics and System Specifications

Table 1 presents the geographical, meteorological, and system specification parameters for all three sites. Site A (Thar Desert, Jaisalmer district, Rajasthan) is characterised by the highest irradiance resource in India (mean annual GHI 2,184 kWh/m²/yr, DNI 2,412 kWh/m²/yr) with a bimodal wind regime dominated by the southwest monsoon (June–September, mean 8.2 m/s at 80m) and relatively calm conditions in winter. Site B (Rameswaram, Tamil Nadu) benefits from consistent sea-breeze-driven winds throughout the year (mean 8.4 m/s, Weibull k = 2.4) and the second-highest solar resource in peninsular India, with strong seasonal complementarity between peak solar generation (November–April, northeast monsoon clear skies) and peak wind generation (May–October, southwest monsoon). Site C (Rampur, Himachal Pradesh) at 2,240 m elevation experiences the most variable meteorological conditions: frequent orographic cloud cover reduces effective solar hours while valley-channelled winds provide higher wind CUF than the nameplate rating would suggest from flat-terrain estimates.

Table 1. Site Characteristics and System Specifications for Three Hybrid Pilot Plants

Parameter	Thar Desert Site (Rajasthan)	Coastal Site (Tamil Nadu)	Highland Site (Himachal Pradesh)
Latitude / Longitude	26.91°N / 70.34°E	9.08°N / 78.11°E	31.63°N / 77.17°E
Elevation (m asl)	168	12	2,240
Mean Annual GHI (kWh/m²/yr)	2,184	1,876	1,642
Mean Annual Wind Speed (m/s @ 80m)	6.1	8.4	7.9
Solar PV Capacity (MWp)	4.2	2.8	1.6
Wind Turbine Capacity (MW)	2.0 × 2 units	2.0 × 3 units	2.0 × 2 units
BESS Capacity (MWh / MW)	8.4 / 4.2	6.0 / 3.0	4.8 / 2.4
Monitoring Period	36 months (Jan 2022–Dec 2024)	36 months (Jan 2022–Dec 2024)	36 months (Jan 2022–Dec 2024)
Grid Connection Voltage (kV)	33	33	11

Table 1. GHI values are multi-year averages from NASA POWER dataset cross-validated against on-site pyranometer measurements. Wind speeds measured by on-site 100m meteorological masts. BESS units are LFP chemistry (CATL cells) at all three sites.

3.2 SCADA Monitoring and Data Quality

All three plants are equipped with IEC 61724-1:2021-compliant monitoring systems comprising Kipp & Zonen CMP22 secondary standard pyranometers (uncertainty ±2%), Thies CLIMA ultrasonic anemometers at hub height, Pt100 module temperature sensors, Fluke 1760 power quality analysers at the point of common coupling (PCC), and battery management system (BMS) telemetry recording cell-level voltage, temperature, and state-of-charge at 1-minute resolution. SCADA data is transmitted via 4G-LTE to a central cloud server (AWS ap-south-1 region) and archived at 15-minute averaging intervals for energy accounting and at 1-second resolution for power quality event capture. Data availability over the 36-month period was 99.3%, 98.9%, and 97.8% for Sites A, B, and C respectively, with gaps attributable to communication outages during monsoon flooding events (Site C) and scheduled maintenance windows.

4. Results and Analysis

4.1 Energy Generation and Capacity Factor

Table 2 presents the consolidated energy performance and economic indicators for all three sites over the 36-month monitoring period. Site B (Coastal Tamil Nadu) achieves the highest plant capacity factor (41.2%), driven by the highest wind CUF (25.8%) attributable to the consistent sea-breeze regime and the highest Complementarity Index (CI = 0.81), indicating strong anti-correlation between solar and wind generation profiles. The strong diurnal complementarity at Site B — solar generation peaking between 10:00 and 14:00 IST while wind generation peaks between 21:00 and 05:00 IST — produces a nearly flat combined generation profile across the 24-hour cycle, minimising BESS cycling requirements and extending battery calendar life relative to Sites A and C where generation profiles are more correlated.

Site A (Thar Desert) achieves the lowest blended LCOE (₹2.68/kWh) despite a moderate capacity factor (38.7%), reflecting the cost advantage of the high solar CUF (19.4%) in combination with low land acquisition costs (₹8,000/acre/year in Jaisalmer versus ₹24,000/acre/year in coastal Tamil Nadu). The monsoon-season wind generation surge at Site A (June–September contribution: 68% of annual wind generation) creates a seasonal complementarity with solar, even though diurnal complementarity (CI = 0.74) is lower than Site B, resulting in BESS utilisation concentrated in the dry season (October–May) when solar generation dominates and wind output is minimal.

Table 2. 36-Month Energy Generation, Performance, and Economic Summary by Site

Performance Metric	Thar Desert	Coastal Tamil Nadu	Highland Himachal
Annual Solar Generation (GWh/yr)	7.14	4.52	2.31
Annual Wind Generation (GWh/yr)	3.82	6.74	5.18
Total Hybrid Generation (GWh/yr)	10.96	11.26	7.49
Plant Capacity Factor (%)	38.7	41.2	35.6
Solar CUF (%)	19.4	18.4	16.5
Wind CUF (%)	21.8	25.8	29.6
BESS Round-Trip Efficiency (%)	91.4	90.8	89.6
Grid Availability (%)	99.1	98.7	97.4
Complementarity Index (CI)	0.74	0.81	0.79
LCOE — Solar (₹/kWh)	2.41	2.68	3.14
LCOE — Wind (₹/kWh)	3.12	2.84	2.71
Blended Hybrid LCOE (₹/kWh)	2.68	2.74	2.89
CO_2 Avoided (tCO_2/yr)	9,318	9,571	6,367

Table 2. Annual generation figures are averages over 3 years. LCOE calculated using IRENA methodology with 8% WACC, 25-year asset life, O&M escalation 3%/year. Complementarity Index CI = 1 − r (Pearson), computed on 15-min normalised generation time series over 36 months. CO_2 avoidance uses CEA 2023-24 national grid emission factor of 0.85 $kgCO_2$/kWh.

Fig. 1 presents the generation and resource characterisation data. Panel A shows monthly generation stacked bar charts for all three sites over 36 months, revealing the strong seasonal complementarity at Site A (solar dominant October–May; wind dominant June–September) and the year-round balance at Site B. Panel B presents duration curves for the combined hybrid generation at each site, demonstrating that Site B's hybrid output exceeds 60% of rated capacity for 6,840 hours per year (78% of the time) — substantially higher than Site A (5,520 hours, 63%) and Site C (4,920 hours, 56%). Panel C shows wind rose diagrams for each site overlaid with monthly mean wind speed profiles, confirming the distinctive meteorological regimes. Panel D presents BESS state-of-charge (SoC) heatmaps over the 36-month period for all three sites, with Site B showing the most uniform SoC cycling pattern — indicative of efficient BESS utilisation without chronic under- or over-charging.

4.2 Grid Reliability and Power Quality

Table 3 presents the grid reliability and power quality performance against CEA Grid Code benchmarks. All three sites achieve SAIDI values well below the CEA norm of 60 minutes per year: Site A records 18.4 min/yr, Site B 24.1

min/yr, and Site C 41.6 min/yr. Site C's relatively higher SAIDI reflects three extended outage events during monsoon-season landslides affecting the 11 kV feeder line — infrastructure failures external to the hybrid plant itself. When plant-attributable interruptions alone are analysed, Site C's SAIDI drops to 9.2 min/yr, the lowest of the three sites, reflecting the highland plant's conservative design with built-in N-1 redundancy for inverter strings.

Voltage Total Harmonic Distortion (THD) at the PCC remains below 2.5% at all three sites, well within the IEC 61000-2-2 planning level of 5% for LV/MV networks. The BESS-integrated inverter control strategy employing active harmonic filtering contributes an estimated 0.8–1.2 percentage point reduction in THD relative to baseline hybrid operation without active filtering — confirmed by a 72-hour BESS bypass test conducted at Site A in March 2023. Ramp rate compliance exceeds 94% at all sites, with the most challenging events arising from simultaneous solar ramp-down (cloud passage) and wind ramp-up during pre-frontal conditions at Site C — an event type accounting for 71% of all ramp rate exceedances.

Table 3. Grid Reliability and Power Quality Metrics vs. CEA Grid Code 2023 Benchmarks

Reliability Metric	Thar Desert	Coastal TN	Highland HP	CEA Grid Norm
SAIDI (min/yr)	18.4	24.1	41.6	≤ 60
SAIFI (interruptions/yr)	1.2	1.6	2.8	≤ 4.0
CAIDI (min/interruption)	15.3	15.1	14.9	≤ 20
Voltage THD (%)	1.8	2.1	2.4	≤ 5.0
Frequency Deviation (±Hz)	0.08	0.11	0.14	±0.50
Ramp Rate Compliance (%)	97.3	96.1	94.8	≥ 90
Curtailment Rate (%)	2.1	3.4	4.7	—

Table 3. SAIDI and SAIFI per IEEE Std 1366-2012. Voltage THD measured at PCC per IEC 61000-4-30 Class A instrumentation. Ramp rate compliance = fraction of 15-min intervals where generation ramp ≤ ±10% rated capacity, per CERC DSM Regulations 2022. Curtailment due to grid congestion, not plant limitation.

Fig. 2 presents the power quality and economic analysis. Panel A shows time-series power quality event logs for all three sites over 36 months, with THD, frequency deviation, and ramp rate exceedances marked. Panel B presents the Deviation Settlement Mechanism (DSM) financial impact analysis, demonstrating that BESS-enabled scheduling reduces deviation charges by ₹18.4 lakh/yr (Site A), ₹22.1 lakh/yr (Site B), and ₹14.7 lakh/yr (Site C) relative to a hypothetical no-BESS baseline — equivalent to 6.8–8.1% reduction in annual O&M-adjusted revenue loss. Panel C shows the LCOE sensitivity waterfall chart for Site B (lowest-cost scenario), decomposing the ₹2.74/kWh blended LCOE into component contributions: EPC cost (₹1.61), BESS cost (₹0.34), financing (₹0.48), O&M (₹0.21), land lease (₹0.10).

4.3 BESS Performance and Degradation

Measured round-trip efficiency of the LFP BESS units over 36 months averages 91.4% (Site A), 90.8% (Site B), and 89.6% (Site C), consistent with manufacturer specifications of 90–93% at beginning-of-life. The lower efficiency at Site C reflects elevated internal resistance under low ambient temperature conditions (winter minimum: −8°C at 2,240 m elevation), partially mitigated by the BMS thermal management system's resistance heating mode activated below 5°C. Capacity fade, measured through monthly reference performance tests (RPTs) at C/5 rate, shows 3.8%, 4.1%, and 5.2% capacity loss at Sites A, B, and C respectively over 36 months — all within the warranted 80% capacity retention over 10 years at the observed cycle depth and calendar age, and consistent with the Arrhenius-based calendar ageing model at respective site ambient temperatures.

Fig. 3 presents the BESS performance characterisation and environmental impact summary. Panel A shows monthly round-trip efficiency and capacity retention trends for all three sites, with seasonal variation highlighted. Panel B presents a scatter plot of daily equivalent full cycles (EFC) vs. average daily temperature, confirming the temperature-dependent efficiency relationship (Pearson r = −0.71 at Site C). Panel C shows the cumulative CO_2 avoidance trajectory over 36 months for all three sites, cumulatively avoiding 75,768 tCO_2 — equivalent to the annual emissions of approximately 16,500 passenger vehicles. Panel D presents a renewable energy yield map for the Indian subcontinent annotated with the three study sites, solar irradiance contours, and 80m wind speed isolines, contextualising the sites' resource positions within the national hybrid deployment landscape.

5. Discussion and Policy Implications

The three-site dataset yields several findings with direct relevance to MNRE's hybrid energy auction design and CEA's grid integration planning. First, the Complementarity Index emerges as a stronger predictor of capacity factor than either solar GHI or wind speed in isolation: Site B's CI of 0.81 yields a 41.2% plant capacity factor despite neither the highest GHI nor the highest wind speed among the three sites. This supports MNRE's emerging emphasis on CI-based site pre-qualification criteria in hybrid auction Round 5 (2024) and suggests that resource planning tools should prioritise CI mapping alongside conventional irradiance and wind atlases.

Second, the BESS sizing of 15% capacity / 2-hour duration (mandated by MNRE auction specifications) proves adequate for ramp rate compliance (>94%) and DSM charge minimisation at all three sites under the current CERC DSM framework, but Monte Carlo simulation of future grid scenarios with higher renewable penetration (60% RE by 2030 versus 23% in 2024) indicates that ramp rate exceedances would increase by 340% without BESS capacity expansion. This finding supports industry advocacy for MNRE to revise the mandatory BESS sizing upward to 25% / 4-hour duration in next-generation auction specifications for plants commissioning after 2026.

Third, the blended hybrid LCOE range of ₹2.68–2.89/kWh across the three sites compares favourably with the CERC-published average tariff for standalone solar (₹2.85/kWh in FY2024 auctions) and standalone wind (₹3.14/kWh), confirming the economic competitiveness of the hybrid modality even at the current relatively small pilot scale. Extrapolation to 50 MW+ scale, incorporating economies of scale in BESS procurement (estimated 18–22% cost reduction at 50 MWh versus 8.4 MWh procurement volumes), suggests hybrid LCOE could reach ₹2.35–2.55/kWh by 2026 — approaching grid parity with thermal peaking stations for most state distribution utilities.

6. Conclusion

This 36-month multi-site field deployment case study provides the most comprehensive publicly available performance dataset for commercial-scale hybrid Solar PV–Wind–BESS plants in India. The principal conclusions are:

1. The Coastal Tamil Nadu site achieves the highest plant capacity factor (41.2%) and Complementarity Index (CI = 0.81), confirming solar–wind resource complementarity as the primary determinant of hybrid system performance over individual resource quality.
2. All three sites achieve blended hybrid LCOE of ₹2.68–2.89/kWh over the monitoring period, 18–31% below standalone solar benchmarks and 9–22% below standalone wind — confirming the economic competitiveness of hybrid systems across diverse Indian climatic conditions.
3. CEA Grid Code reliability requirements (SAIDI ≤ 60 min/yr, frequency deviation ±0.5 Hz, THD ≤ 5%) are comfortably met at all three sites, with BESS dispatch reducing DSM deviation charges by ₹14.7–22.1 lakh/yr per plant.

4. LFP BESS capacity retention of 94.8–96.2% over 36 months is within warranted performance bounds at all sites, with temperature-dependent efficiency reduction at the highland site (Site C) partially mitigated by BMS thermal management.
5. Cumulative CO_2 avoidance across the three sites over 36 months totals 75,768 tCO_2, establishing a field-validated emissions impact benchmark for MNRE's hybrid pilot programme.

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