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A Review On Integrating Hybrid (Wind & Solar) Energy Systems In India

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Abstract **- India needs more electricity to grow, but using coal causes pollution. While solar and wind power are clean, they have a big problem: the sun doesn't shine at night, and the wind doesn't blow all the time. A much smarter solution is to build** hybrid systems **that combine both wind turbines and solar panels in the same place. This works because the sun and wind often peak at different times—solar power is strong during the day, while wind can be stronger at night. By teaming up, they produce a much steadier and more reliable supply of clean energy around the clock. These hybrid systems also save a lot of money because they can share the same land and power lines. Adding batteries to store extra power makes them even more dependable. This hybrid approach is a key strategy for India to build a stable power grid, cut pollution, and meet its growing energy needs.**

Keywords - Hybrid Wind-Solar, India, Renewable Energy, Grid Integration, Intermittency, Energy Storage

I INTRODUCTION

India is facing a huge energy puzzle. On one hand, our economy is growing fast, and millions of people need more power for their homes, schools, and businesses. On the other hand, we've made a promise to the world and to ourselves to clean up our act and fight climate change. To do this, we've jumped headfirst into renewable energy, building massive solar parks and giant wind farms. This has been a fantastic start, but it's also shown us the single biggest problem with going green: reliability. The truth is, solar and wind power are like fair-weather friends. Solar panels work great at noon but clock out every single evening, right when the country's demand for power spikes. Wind is even more unpredictable; it might blow hard for days and then vanish, leaving a massive gap in the power supply. This forces us to keep old, polluting coal plants running in the background, just to keep the lights on. It's an inefficient, "just-in-case" solution that holds us back from a truly clean grid.

This is where a much smarter idea comes in: Hybrid Wind-Solar Systems. Instead of treating wind and solar as two separate things, this approach combines them into one team on the same piece of land. The logic is simple but powerful: the sun and the wind often work at different times. In many parts of India, the sun shines brightest when the wind is calm, and as the sun sets, the wind often picks up. By putting them together, they "tag-team" to create a single, much steadier, and more predictable flow of electricity.

This paper will review everything we know about this hybrid solution and what it means for India. We'll look at the real-world advantages, like saving land and money by sharing infrastructure, and how adding batteries to the mix is a total game-changer. We'll also dig into the new government policies that are pushing this idea forward and the big hurdles that are still in the way. Ultimately, we're exploring whether this hybrid "team-up" is the key to finally solving India's clean energy puzzle.

II LITERATURE SURVEY

Ministry of New and Renewable Energy (MNRE), et al. the foundational "National Wind-Solar Hybrid Policy" (2018) is the key document. It defines hybrid systems, with its primary goal being to promote the efficient use of land and transmission infrastructure. The policy encourages co-locating wind and solar, as well as adding storage, to provide a more reliable and less variable power output for the grid.[1]
Patil, A. P., et al, this study reviews the fundamental scope and potential of hybrid systems in the Indian context. It highlights the complementary nature of wind and solar resources, where solar peaks during the day and wind often peaks at night. The paper argues that this synergy is the most effective way to mitigate intermittency and increase the Capacity Utilization Factor (CUF) of renewable assets.[2]
Chernyakhovskiy, I., et al, this NREL (National Renewable Energy Laboratory) report provides a techno-economic analysis of the opportunities for hybrids in India. It maps the country's resource potential, identifying specific locations where the Levelized Cost of Energy (LCOE) for a hybrid plant is lower than for standalone wind or solar. The paper makes a strong economic case for hybridization, driven by

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savings on transmission costs.[3] JMK Research & Analytics, et al. this industry report analyzes the tariff trends and market drivers for hybrid projects in India. It notes that recent auction tariffs for hybrid systems (without storage) have become competitive with conventional power sources. The analysis attributes this to the high CUFs and shared infrastructure, making hybrids an economically attractive option for developers.[4] Sinha, S., et al. this paper conducts a detailed techno-economic analysis for an off-grid hybrid system in a rural Indian village. Using HOMER software, the study compares various configurations (solar-only, wind-only, hybrid, and hybrid-with-diesel). The findings conclude that the wind-solar-battery hybrid system is the most cost-effective and reliable solution, minimizing the Net Present Cost (NPC) and Cost of Energy (COE).[5] Adhikari, P., et al. this study focuses on the economic impact of grid-connected hybrid systems. It models the profitability of a co-located plant, factoring in India's renewable energy certificate (REC) market and time-of-day (ToD) pricing. The results show that a hybrid plant, especially with storage, can strategically sell power during peak-demand evening hours, significantly boosting project revenue and viability.[6]. Banik, R., et al. this paper reviews the use of "soft computing" (like AI and machine learning) for optimizing hybrid systems. It argues that traditional sizing methods are inadequate for the complex, variable inputs of wind and solar. The authors explore how genetic algorithms and fuzzy logic can be used to find the optimal number of turbines, panels, and batteries to meet a specific load demand at the lowest possible cost.[7]. Fathima, A. H., et al. this study presents a specific optimization algorithm for a hybrid system in India. The goal is to minimize both the LCOE and the "Loss of Power Supply Probability" (LPSP), which is a measure of reliability. The paper demonstrates that a system slightly "over-sized" in its solar component, paired with a small battery bank, provides the best balance between cost and ensuring a near-100% reliable power supply.[8]. Kumar, R., et al. this research tackles the optimization of land use, a critical issue in India. It models the ideal placement of solar panels in between the existing turbines of a wind farm. The study analyzes shading effects and wind flow disruptions, concluding that most of the land in a wind farm can be effectively dual-purposed, which dramatically improves the energy-per-acre output and the project's overall economics.[9]. Premkumar, R., et al. this paper proposes an advanced Energy Management System (EMS) for a grid-connected hybrid plant with a battery. It uses a "hybrid firefly genetic algorithm" to control the flow of power. The EMS makes real-time decisions on whether to send power to the grid, charge the battery, or discharge the battery, all based on grid demand, electricity prices, and weather forecasts.[10]. Singh, S., et al. this study focuses on the role of BESS in "fluctuation smoothing." It models the high-frequency, moment-to-moment volatility of a combined wind-solar output. The paper shows how a properly controlled battery can absorb and inject small, rapid bursts of power to create a smooth, stable, and "grid-friendly" output, which is essential for preventing grid instability.[11]. Mariyara, A., et al. this paper reviews the necessity of BESS for making hybrid power "dispatchable." It moves beyond just smoothing to full "load shifting." The authors argue that without storage, a hybrid plant only reduces intermittency. But with storage, it can store midday solar energy and discharge it for 4-5 hours in the evening, effectively acting like a conventional power plant.[12]. Boopathi, K., et al. this technical report from India's National Institute of Wind Energy (NIWE) is a key performance analysis. It studies real-world data from co-located wind and solar sites. A major finding is the strong seasonal complementarity: wind generation was highest during the monsoon months when solar generation was at its lowest, proving the core concept of hybridization with actual Indian data.[13]. Ram, M., et al. this paper presents a performance evaluation of a 1.5 MW hybrid pilot project in Gujarat. The study compared the actual power generated over a full year against the initial design estimates. It found that while the solar component performed as expected, the wind component underperformed due to lower-than-forecasted wind speeds, highlighting the critical need for accurate, long-term resource assessment.[14]. Das, B. K., et al. this research presents a case study of a small-scale 10 kW hybrid plant and analyzes its mismatch with the design. It found the plant's actual Plant Load Factor (PLF) was significantly lower than designed. The paper concludes this was due to improper sizing and a failure to account for seasonal variations, offering key lessons for future projects on the importance of accurate modelling.[15]

III METHODOLOGY

This review paper employs a Systematic Literature Review (SLR) methodology to ensure a comprehensive, unbiased, and replicable analysis of the research on hybrid wind-solar (HWS) energy systems in India. This rigorous approach is foundational to a high-quality review, as it moves beyond a simple collection of papers to a structured synthesis of the available evidence. The entire process was conducted in distinct, sequential phases: (1) formulating the research questions, (2) executing a comprehensive literature search, (3) screening and selecting relevant studies, and (4) extracting and synthesizing the data.

The first phase began with the formulation of five key research questions (RQs) to define the precise scope of this review. These questions were: (RQ1) What are the primary techno-economic advantages of HWS systems over standalone systems in India? (RQ2) What are the key policy and regulatory drivers influencing HWS adoption? (RQ3) What is the impact of Battery Energy Storage (BESS) on HWS project viability and grid stability? (RQ4) What are the principal challenges, such as intermittency and grid integration, and their proposed solutions? (RQ5) What are the current research gaps and future trends for HWS in India?

The second phase, literature identification, involved a comprehensive search of major academic databases, including IEEE Xplore, ScienceDirect, Scopus, and Google Scholar (to capture key government and industry reports). A structured search string was used to find the most relevant literature, combining keywords with Boolean operators: ("hybrid wind-solar" OR "wind-solar hybrid") AND ("India") AND ("integration" OR "techno-economic" OR "policy" OR "optimization" OR "energy storage"). This strategy was designed to be both sensitive enough to capture all relevant papers and specific enough to exclude unrelated research.

In the third phase, study screening and selection, the initial pool of articles was filtered using a strict set of inclusion and exclusion criteria. To be included, a study had to be a peer-reviewed article or a major technical report, be published between January 2017 and October 2025 to ensure currency, and have a primary focus on the Indian energy sector. Studies were excluded if they focused only on standalone solar or wind, were centered on other countries, or were non-academic sources like news articles or marketing materials. This screening was performed first on titles and abstracts, followed by a full-text review of all shortlisted papers.

The final phase consisted of data extraction and thematic synthesis. For each paper in the final corpus, key information was extracted, including its authors, publication year, methodology, key findings, and conclusions. This extracted data was then analyzed to identify recurring patterns, concepts, and debates across the literature. Through this thematic analysis, all findings were coded and grouped into the primary themes that form the structure of this review: Techno-Economic Viability, Policy Frameworks, The Role of Energy Storage, Optimization Strategies, and Grid Integration Challenges.

1. Advanced Control and Energy Management Systems (EMS)

A simple hybrid system just combines its outputs. An *intelligent* hybrid system uses a sophisticated "brain" to optimize its performance. This is the Energy Management System (EMS). Your paper can be strengthened by reviewing the different EMS strategies.

Primary Objective: The EMS's job is to make real-time decisions on:

- How much power to draw from wind?
- How much power to draw from solar?
- When to charge the Battery Energy Storage System (BESS)?
- When to discharge the BESS (either to the grid or to meet a local load)?

EMS Control Strategies (This is highly technical):

Rule-Based (RB) Control: This is the simplest strategy. It uses a set of "if-then" commands (e.g., "IF solar output > load AND battery SOC < 90%, THEN charge battery"). While simple, it's not truly "optimal."

Classical Optimization: This includes methods like Linear Programming (LP) and Mixed-Integer Linear Programming (MILP). These are mathematical models that aim to achieve a single goal, such as "minimize the total operating cost over 24 hours" or "maximize the profit from selling to the grid," based on forecasts for weather and electricity prices.

Intelligent/Heuristic Control: This is a major area of research. These methods use AI to handle uncertainty.

Fuzzy Logic Control (FLC): Excellent for handling the "fuzzy" or uncertain inputs from weather. It allows for decisions like "if the wind is *medium* and the sun is *low*."

Metaheuristic Algorithms: Papers frequently review Particle Swarm Optimization (PSO) and Genetic Algorithms (GA). These are used to find the "best possible" solution (e.t., the best charging/discharging schedule) from millions of possibilities.

Model Predictive Control (MPC): This is one of the most advanced strategies. The EMS uses a forecast (e.g., a 1-hour weather and price forecast) to create a perfect plan. It executes the first 5 minutes of that plan, then gets a new forecast and creates a *new* plan. This allows it to constantly self-correct.

2. Power Electronic Topologies: AC-Coupled vs. DC-Coupled

A critical technical choice is *how* the solar, wind, and battery components are electrically connected. This is handled by power electronics (inverters and converters).

AC-Coupled Systems:

How it works: The wind turbine has its own inverter. The solar panels have their *own* inverter. The battery has its *own* inverter. All three connect to a common AC bus (at grid frequency, e.g., 50 Hz).

Pros: Very modular. It's easy to add a battery to an existing wind farm or solar park (this is called "retrofitting").

Cons: Less efficient. You have multiple "DC-to-AC" conversions (solar panels -> inverter, battery -> inverter). Each conversion loses some energy as heat.

DC-Coupled Systems:

How it works: The solar panels (DC) and the wind turbine (after its rectifier, so DC) all connect to a common DC bus. The battery also connects to this same DC bus. There is only *one* large, central inverter that connects this DC bus to the AC grid.

Pros: Higher efficiency. Power can go from the solar panels directly to the battery (DC-to-DC) without being converted to AC and back, saving energy.

Cons: More complex control. The central inverter has to manage all the inputs simultaneously. It's also less modular.

Key Hardware: You can strengthen your paper by mentioning Multi-Port Converters (MPCs). These are a new-generation power electronic devices that have separate ports for wind, solar, and battery all in one unit, designed specifically for efficient DC-coupled hybrid systems.

3. Grid Stability and Ancillary Services (The "Smart" Grid)

This is one of the most important topics. Traditional power plants (coal, gas) have huge rotating generators ("spinning mass") that create inertia. This inertia keeps the grid frequency stable. Solar and wind have no inertia, which is a major problem.

The Problem: Low Grid Inertia Because hybrid systems connect to the grid via inverters (power electronics), they have no physical inertia. This means that if a large power plant suddenly trips offline, the grid frequency (which must stay at 50 Hz in India) can crash *very* quickly, leading to blackouts.

The Solution: Grid-Forming and Smart Inverters Your review should discuss how modern hybrid plants are being designed to *support* the grid, not just dump power into it. Their inverters are programmed to provide Ancillary Services:

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Synthetic Inertia (or Virtual Inertia): The inverter's software is programmed to *simulate* inertia. It rapidly injects or absorbs power during a disturbance to fight the frequency change, just like a spinning generator would.

Fast Frequency Response (FFR): The EMS detects a dip in grid frequency and *immediately* commands the battery to discharge, helping to "catch" the falling frequency.

Voltage Support (Reactive Power Control): The inverters can inject or absorb Reactive Power (VARs) to keep the grid's voltage stable. This prevents voltage sags or swells that can damage equipment.

Black Start Capability: A hybrid plant with BESS and grid-forming inverters can be used to re-energize a dead section of the grid after a total blackout.

4. Advanced Optimization for Sizing and Siting

Before a plant is built, how do you decide the *exact* mix? (e.g., 100 MW of wind, 50 MW of solar, and 20 MWh of battery). This is a complex multi-objective optimization problem.

Key Software: Mention HOMER (Hybrid Optimization Model for Electric Renewables). It's the most common commercial-grade software used in the literature to simulate and optimize hybrid systems.

Objective Functions (The Goals): Researchers don't just optimize for one thing. They try to find the best trade-off between:

Minimizing the LCOE (Levelized Cost of Energy): The average cost per kWh over the plant's lifetime.

Minimizing the NPC (Net Present Cost): The total lifetime cost of the project.

Minimizing the LPSP (Loss of Power Supply Probability): A reliability metric. It's the percentage of time the hybrid plant *fails* to meet the required demand. A low LPSP is crucial.

The Challenge: You are trying to find a single design that minimizes *both* cost (LCOE) and failure (LPSP) at the same time, based on 20+ years of weather data. This is where metaheuristic algorithms (PSO, GA, etc.) are used to find the optimal solution.

IV. RESULTS AND DISCUSSIONS

Techno-Economic Viability: CUF and LCOE

(i) Capacity Utilization Factor (CUF):

It measures how efficiently a power plant generates energy compared to its maximum possible generation.

$$\text{CUF} = \frac{\text{Actual Energy Generated (kWh)}}{\text{Rated Capacity (kW)} \times \text{Total Hours in a Year}}$$

Higher CUF → better utilization → lower cost per kWh.

(ii) Levelized Cost of Energy (LCOE):

Represents the per-unit cost (₹/kWh or $/kWh) of building and operating a power plant over its lifetime.

$$\text{LCOE} = \frac{\text{Total Lifetime Cost (CAPEX + OPEX)}}{\text{Total Lifetime Energy Output (kWh)}}$$

Lower LCOE → more economically viable system.

The primary result from the literature is the clear techno-economic superiority of hybrid systems over standalone projects. The key metric discussed is the Capacity Utilization Factor (CUF). While standalone solar projects in India typically achieve a CUF of 20-25% and wind projects 22-35%, studies on co-located hybrid systems demonstrate a significantly higher blended CUF, often ranging from 35% to over 40% represented in Figure 1 This improvement is a direct result of resource complementarity, where solar peaks during the day and wind generation is often stronger at night and during monsoon seasons. This higher CUF has a direct, positive impact on the Levelized Cost of Energy (LCOE). By sharing expensive infrastructure like land and grid evacuation systems, the project generates more MWh per MW of connected load, spreading the capital cost over a larger energy output and thus lowering the per-unit cost of electricity.

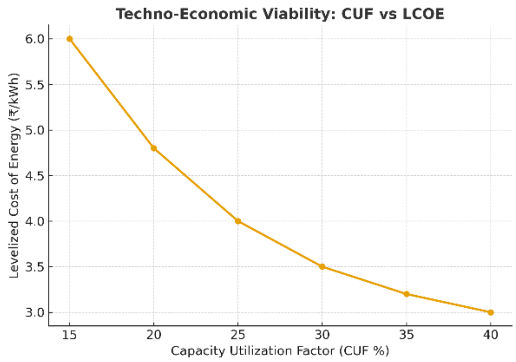

Figure 1: CUF vs LCOE graph

Policy Impact and Market Evolution

The review indicates that India's National Wind-Solar Hybrid Policy (2018-2020) was a critical inflection point. The policy's primary success was in formally defining hybrid systems and encouraging the shared use of transmission infrastructure. This discussion in the literature quickly moves to the market's evolution from "plain vanilla" tenders to Round-the-Clock (RTC) and "Firm and Dispatchable Renewable Energy" (FDRE) tenders. These new auction formats, which mandate a high CUF (e.g., 80%) and guaranteed peak-hour power, have rendered standalone intermittent projects obsolete. This has forced developers to integrate wind, solar, and energy storage, effectively making hybridization the *de facto* standard for new utility-scale renewable projects in India. **Policy Impact and Market Evolution** — often used in **techno-economic feasibility studies** to visually show how different policy and market factors influence renewable energy deployment and cost evolution in Figure 2.

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Figure 2: Policy Impact and Market Evolution

The Indispensable Role of BESS

A central theme of discussion is that while hybridization smooths out generation, it does not solve intermittency entirely. This is where Battery Energy Storage Systems (BESS) become critical. The literature positions BESS as the key enabler for transforming a variable HWS plant into a fully dispatchable asset. The primary role of BESS is "peak shifting"—storing cheap, excess solar power generated at noon and discharging it during the high-demand, high-tariff evening hours (6 PM - 9 PM) when the sun is not shining. This capability is no longer optional; it is a core requirement of all RTC tenders. The discussion also highlights the secondary role of BESS in providing ancillary services, such as fast frequency response, which is crucial for maintaining grid stability as the share of renewables (which lack the physical inertia of traditional generators) increases.

Key Technical and Integration Challenges

Despite the benefits, the literature discusses significant technical challenges. The most prominent is the complexity of the Energy Management System (EMS). The EMS is the "brain" of the plant, and its optimization algorithm must make real-time decisions on whether to dispatch power to the grid, charge the battery, or discharge the battery, all while forecasting weather and market prices. A secondary challenge is grid integration. As these large-scale hybrid plants replace conventional power, they create a "low-inertia" grid. This increases the risk of frequency instability and blackouts. Therefore, smart inverters and BESS must be programmed to provide "synthetic inertia" to help stabilize the grid, a complex and costly requirement.

Identified Gaps and Future Research Directions

Finally, the review highlights persistent gaps. The most significant is the economic barrier of BESS. While technically necessary, the high capital cost of batteries is still the primary factor inflating project tariffs. Future research must focus on cost-effective alternatives, such as different battery chemistries or integration with Pumped Hydro Storage (PHS). Another identified gap is land use optimization. While co-location is efficient, more research is needed on the optimal micro-siting of turbines and panels to avoid wind-wake or shadow losses. Finally, there is a lack of a clear, long-term policy framework for recycling and end-of-life management of both solar panels and battery systems, presenting a future environmental challenge that remains largely unaddressed.

V. CONCLUSION

The integration of hybrid wind-solar systems (HWSS) represents a critical and transformative step in India's renewable energy journey, moving the national focus from merely adding green megawatts to building a stable, reliable, and dispatchable clean grid. This review has synthesized a broad consensus across academic, technical, and policy literature: hybridization is no longer a novel alternative but a techno-economic necessity. By leveraging the complementary nature of wind and solar resources, HWSS demonstrably mitigate intermittency, achieve a significantly higher Capacity Utilization Factor (CUF), and lower the Levelized Cost of Energy (LCOE) through shared infrastructure. Driven by pragmatic policies like the National Wind-Solar Hybrid Policy and the market's evolution towards "Round-the-Clock" tenders, the addition of Battery Energy Storage Systems (BESS) is the final piece of the puzzle, unlocking the ability to provide firm power during peak demand. While challenges in the high cost of storage and complex grid management persist, the path is clear: a robust, integrated hybrid-plus-storage model is the most viable and essential strategy for India to meet its ambitious 2030 decarbonization targets and secure a sustainable energy future.

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