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Unlocking India's Energy Transition
Addressing Grid Flexibility Challenges and Solutions

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Key Takeaways

- India is racing toward a 500 GW renewable energy target by 2030 but achieving this will require a massive ₹2,442 billion (€26.86 billion) investment in grid expansion.
- Storage remains a bottleneck—India has just 4.7 GW of pumped hydro and 219 MWh of battery energy storage systems (BESS) as of March 2024, far from the 60.63 GW goal for 2030, with 41.65 GW expected from BESS alone.
- The corporate Power Purchase Agreement market is surging, fueled by commercial and industrial demand, with capacity projected to hit 80 GW by 2030. However, policy volatility, high open access charges, and distribution companies hurdles persist.
- Unlocking India's energy future hinges on regulatory stability, stronger financial de-risking mechanisms, and rapid smart meter deployment to modernize the grid and attract private investment.

Introduction

India is rapidly scaling up its renewable energy (RE) capacity, adding 15–20 GW annually, but the ambitious goal of 500 GW of non-fossil capacity by 2030 is at risk unless the pace accelerates. This green transition is revealing significant vulnerabilities in the national grid. Solar and wind energy, with their inherent variability, depend on unpredictable weather patterns, unlike traditional power plants. This challenge is magnified by India's tight operating frequency band of 49.90 Hz to 50.05 Hz,[1] where even slight fluctuations can cause grid instability. To make matters worse, climate change is heightening the grid's vulnerability.

Transmission bottlenecks and geographic mismatches are adding to the challenge. While the country's richest renewable resources are concentrated in Rajasthan, Gujarat, and Tamil Nadu, the highest demand is in industrial centers and densely populated regions like Delhi-NCR, Maharashtra, and West Bengal. The transmission network struggles to keep up, resulting in congestion and curtailment, where clean energy is available but cannot be delivered. For instance, on August 11, 2022, India lost 6 GW of RE due to frequency and voltage instability.[2] Without significant upgrades, such incidents are likely to increase.

Expanding on the author's previous policy brief on the financial struggles of India's state-run Distribution Companies (DISCOMs), this analysis connects their persistent losses to the growing instability in the power grid caused by rapid RE expansion. As DISCOMs grapple with unreliable service, the absence of grid flexibility and storage investments is only worsening their financial stress. This brief explores actionable solutions–from strengthening transmission infrastructure to deploying innovative market mechanisms–that can fortify India's grid, ensuring a clean energy transition that is both ambitious and resilient.

India's power grid struggles with RE expansion

India's grid is interconnected and operates as a unified national electricity grid. Full integration was achieved in 2013 with the synchronization of the Southern Grid with the rest of the national grid, allowing power transfers across all five regional grids (Northern,

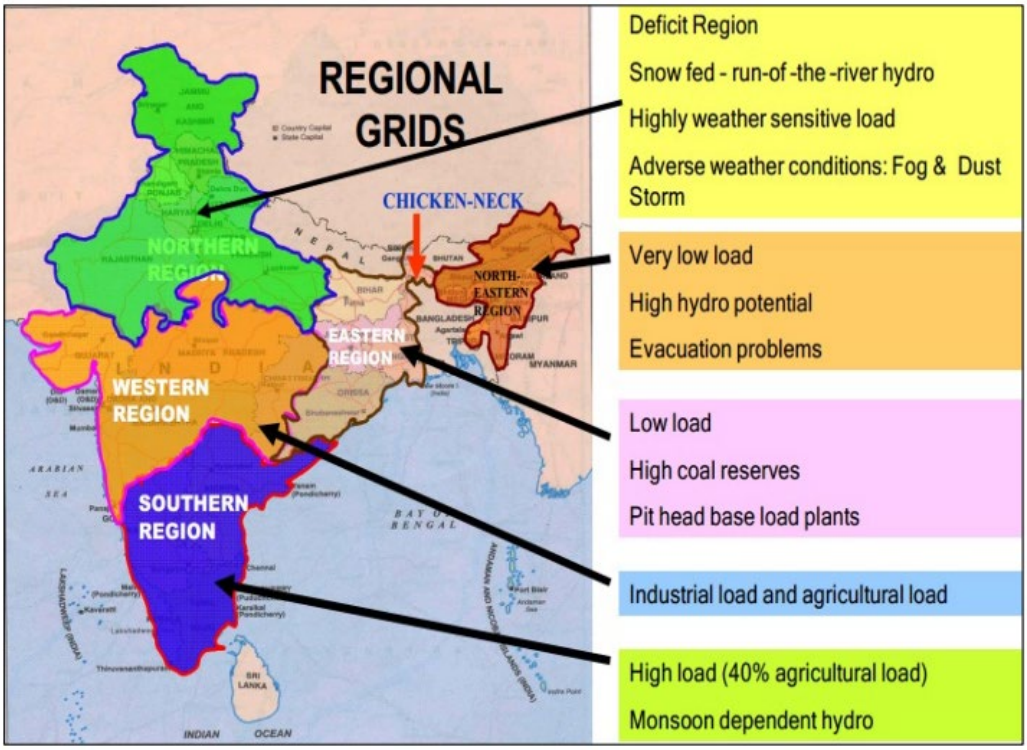
1. "Annexure 1: Power Sector Overview", Central Electricity Regulatory Commission (CERC), 2016, available at: https://cercind.gov.in.

2. "Analysing Grid Events: Report on Transmission System Faults Leading to Renewable Energy Loss", Power Line, 2024, available at: https://powerline.net.in.

Eastern, Western, Southern, and North-Eastern).[3] However, challenges remain in effectively evacuating RE from generation-rich regions to high-demand centers.

India's RE generation is concentrated in a few states—Rajasthan (33.15 GW), Gujarat (32.30 GW), Tamil Nadu (24.33 GW), Karnataka (23.02 GW), Maharashtra (20.98 GW), and Andhra Pradesh (11.18 GW)—which collectively account for the bulk of the country's solar and wind capacity[4]. However, demand centers like Delhi-NCR, Uttar Pradesh, Punjab, Haryana, West Bengal, and Bihar are located far from key generation hubs, underscoring the urgent need for a robust transmission network to ensure efficient power evacuation.

Figure 1: Characteristics of regions in terms of generation and demand



Source: Power System Operation in India – Few Challenges. WRLDC-TP-055. SECS 2014. Available at: https://posoco.in.

Tamil Nadu, part of the Southern Region Grid, faces a mismatch between wind generation (which peaks from May to September) and local demand. This leads to up to 15-20% curtailment due to inadequate transmission and storage. Similarly, Karnataka and Andhra Pradesh face challenges with intermittent solar generation, experiencing 50-70% drops during monsoons, which forces greater reliance on fossil fuel plants. Andhra Pradesh and Telangana also experience seasonal fluctuations, with high wind generation in certain months leading to oversupply and curtailment, while winter months require backup thermal power.

3. "RLDC TP 055 - Power System Operation in India: Few Challenges – SECS 2014", Power System Operation Corporation Limited (POSOCO), 2020, available at: https://posoco.in.

4. "Figures & Statistics", National Solar Energy Federation of India (NSEFI), n.d., available at: www.nsefi.in.

Rajasthan, in the Northern Region Grid, experiences solar fluctuations that create grid instability, forming the "duck curve"—with excess generation at midday and shortfalls in the evening, increasing reliance on fossil fuel plants. Rajasthan's 23 GW solar capacity often overloads transmission infrastructure, causing 5-10% curtailment during peak sunlight hours.

Strengthening grid infrastructure and energy storage

According to the Central Electricity Authority (CEA), integrating over 500 GW of RE capacity by 2030 will require a massive expansion of India's transmission infrastructure. This includes building 50,890 circuit kilometers (ckt km) of Interstate Transmission System (ISTS) lines and adding 433,575 MVA of substation capacity to efficiently transfer wind and solar power across the grid. Key developments in the plan include transmission corridors for 10 GW of offshore wind energy from Gujarat and Tamil Nadu, and significant additions such as 8,120 ckt km of HVDC lines, 25,960 ckt km of 765 kV AC lines, and 15,758 ckt km of 400 kV lines. The estimated investment required for these upgrades is ₹2,442 billion (€26.86 billion),[5] highlighting the urgent need to strengthen grid infrastructure to support India's RE ambitions.

To address transmission bottlenecks, the Green Energy Corridor (GEC) was launched in 2015. Focused on enhancing both inter-state and intra-state grids, GEC has a total budget of ₹11,369 crore (€1.25 billion). It involves setting up RE Management Centers and deploying reactive compensation and storage systems. The ISTS component of the GEC was completed by March 2020, adding 3,200 ckt km of lines and 17,000 MVA of substations.[6] However, delays persist as RE projects, with a gestation period of 18–24 months, frequently outpacing transmission network development, which takes 18–30 months.

Recognizing the urgency of modernization, the Ministry of Power established a Task Force in September 2021, chaired by POWERGRID's CMD, to future-proof India's transmission system. The Task Force's 2023 report outlines strategies to enhance efficiency through automation and smart grid technologies. As part of this initiative, control centers have been set up to remotely operate Extra High Voltage substations, increasing automation in grid management.[7] Additionally, Artificial Intelligence and Machine Learning-driven predictive maintenance are being implemented in grid substations, with real-time sensors monitoring critical transmission parameters to optimize performance and reliability.

5. "Transmission Plan for 500 GW Non-fossil Capacity by 2030", Central Electricity Authority, 2022, available at: https://cea.nic.in.

6. "Green Energy Corridor", Ministry of Power, n.d., available at: https://powermin.gov.in.

7. "Press Release", Press Information Bureau, 2023, available at: https://pib.gov.in.

The role of battery energy storage systems (BESS)

According to the International Energy Agency, India is poised to become the third-largest market for utility-scale batteries by 2030.[8] However, the country's energy storage infrastructure remains severely underdeveloped. The CEA projects that by 2029-2030, India will need 60.63 GW of energy storage capacity to meet peak demand and stabilize the grid. This includes 18.98 GW from pumped storage (PSP) and 41.65 GW from BESS, amounting to a total energy storage need of 336.4 GWh—128.15 GWh from PSP and 208.25 GWh from BESS.[9] In stark contrast, as of March 2024, India has only 4.7 GW of pumped hydro storage and a mere 219 MWh of battery storage.[10]

To address this significant gap, the Indian government has introduced the Viability Gap Funding (VGF) Scheme for BESS. With an initial outlay of ₹9,400 crore (€1.04 billion), the scheme aims to support the development of 4 GWh of BESS capacity by 2030-2031. By covering up to 40% of the capital cost, it reduces investment risks and lowers the Levelized Cost of Storage to ₹5.50-₹6.60/kWh (€0.061-0.073/kWh).[11] Public and private sector entities will be selected through a competitive bidding process, with projects approved between 2023-2024 and 2025-2026, and funding disbursed until 2030-2031.

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In parallel with the VGF, the government is focusing on reducing import reliance through the Production Linked Incentive (PLI) Scheme for Advanced Chemistry Cell (ACC) Battery Storage, with an outlay of ₹18,100 crore (€1.99 billion). This scheme targets 50 GWh of ACC and 5 GWh of ACC manufacturing, and aims to attract ₹45,000 crore (€4.95 billion) in investments. It also mandates 60% domestic value addition within five years, with manufacturers committing to ₹225 crore (€24.75 million) per GWh in investments.[12]

While the VGF and PLI schemes are crucial for improving the financial viability of BESS, their total allocation is still just a fraction of the ₹96,350 crore (€10.60 billion)

8. "India May Become 3rd Largest Market for Utility-Scale Batteries by 2030: IEAf", *The Hindu Business Line*, 2023, available at: www.thehindubusinessline.com.

9. "National Framework for Promoting Energy Storage Systems", Ministry of Power, 2023, available at: https://powermin.gov.in.

10. "India's Energy Storage Capacity Reaches 219 MWh in March 2024", *The Hindu Business Line*, 2024, available at: www.thehindubusinessline.com.

11. "Press Release", Press Information Bureau, 2024, available at: https://pib.gov.in.

12. "Cabinet approves PLI Scheme for ACC Battery Storage", Press Information Bureau, 2025, available at: https://pib.gov.in.

required to meet the ambitious 41 GW BESS target. This underscores the urgent need for increased funding and enhanced private-sector participation to ensure India achieves its energy storage goals.

Demand-side solutions for grid optimization

The large-scale adoption of demand-side management (DSM) measures, such as Time-of-Day (ToD) pricing and smart metering, is set to become a critical feature of India's energy landscape. With RE sources like wind and solar expected to account for nearly 50% of India's electricity generation by 2030, up from just over 30% in 2024,[13] DSM initiatives will be crucial in integrating these variable resources into the grid.

Time-of-day (ToD) pricing: enhancing cost efficiency and grid stability

ToD pricing creates a win-win situation: consumers enjoy lower costs during solar hours, and the grid remains stable by reducing demand during high-cost peak times. As outlined in the Electricity (Rights of Consumers) Rules 2020, the phased implementation of ToD tariffs is already underway. Starting in 2024, commercial and industrial (C&I) consumers with demand exceeding 10 kW must adopt ToD tariffs, with wider implementation expected by 2025. This regulatory shift will ensure that tariffs during peak hours are at least 1.2 times the normal rate for C&I consumers, with solar hours offering discounts of at least 20%.[14]

Smart metering: empowering consumers, strengthening utilities

India's smart metering drive, spearheaded under the Revamped Distribution Sector Scheme (RDSS), aims to modernize power distribution, reduce billing inefficiencies, and curb financial losses in the electricity sector. By replacing traditional meters with smart meters, the initiative seeks to improve demand-side management, enhance revenue collection, and lower aggregate technical and commercial (AT&C) losses for state-run DISCOMs.

However, the rollout of smart meters has not been uniform. Some states have made significant progress, while others face delays due to administrative and operational hurdles. Assam, Bihar, Chhattisgarh, and Madhya Pradesh have led the way, benefiting from efficient procurement and strong vendor partnerships–particularly with

13. "Power Sector at a Glance", Ministry of Power, n.d., available at: https://powermin.gov.in.

14. "Press Release", Press Information Bureau, 2024, available at: https://pib.gov.in.

IntelliSmart, a key private player in the sector. In contrast, Kerala, Tamil Nadu, Rajasthan, and Punjab have yet to install any smart meters, while Maharashtra lags significantly, having installed only 403,000 meters compared to the 22.49 million sanctioned.[15]

Smaller states have advanced faster, benefiting from fewer administrative roadblocks and prior experience with metering pilots. Meanwhile, larger states with more complex grids are grappling with procurement bottlenecks and infrastructure readiness challenges. Looking ahead, acceleration is expected in Maharashtra and Rajasthan as pending contracts move forward.

Corporate PPAs and the shift to power exchanges

India's corporate Power Purchase Agreement (PPA) market has experienced impressive growth, positioning the country as the second-largest global market for corporate PPAs in 2019, after the United States, according to Bloomberg New Energy Finance.[16] This surge in demand is primarily driven by C&I consumers, who account for 40-45% of India's total energy consumption. With businesses facing increasing pressure to meet sustainability targets and net-zero goals, C&I demand for RE is expected to reach 80 GW by 2030.[17]

The adoption of corporate PPAs is further accelerated by the proactive efforts of states such as Uttar Pradesh and Haryana, which have approved large-scale group-captive solar projects exceeding 1 GW. Industries spanning automotive, IT, electrical manufacturing, construction, and metals are at the forefront of this shift, driving the widespread adoption of corporate PPAs.

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However, several challenges remain. State-level policy fluctuations, particularly regarding open access charges and grid connectivity regulations, continue to create an uncertain environment. For example, Karnataka's recent invalidation of the Green Energy Open Access Rules underscores the volatility of local policies.[18] Moreover, high open access charges, such as cross-subsidy surcharges (CSS), can comprise up to 40-50% of

15. "Smart Meter Statistics", National Smart Grid Mission, n.d., available at: https://www.nsgm.gov.in.

16. "Corporate Renewable PPAs in India, January 2021", World Business Council for Sustainable Development, 2023, available at: www.wbcsd.org.

17. "RE Capacity Requirement from the ICRA Report", ICRA, 2024, available at: www.icra.in.

18. "Karnataka HC Strikes Down Central Rules on Green Energy Open Access", *Business Standard*, 2025, available at: www.business-standard.com.

the total tariff[19], making RE less competitive. While the National Tariff Policy aims to gradually reduce CSS, uneven implementation across states adds complexity. Additionally, securing DISCOM approval for open access remains a hurdle, particularly when local substations lack the technical capacity to accommodate power from industrial solar systems.

In 2022, while 15 GW of RE capacity was planned, only 9.5 GW PPAs were signed, resulting in delays of 6-12 months. Similarly, in 2023, 18 GW was planned, but only 12 GW of PPAs were signed, with delays ranging from 8-10 months. In 2024, delays persisted, ranging from 4 to 8 months.[20]

To unlock the full potential of India's corporate PPA market, India needs standardized PPA structures and clearer frameworks for Renewable Purchase Obligation compliance at the state level. Creating a stable and predictable regulatory environment is crucial to attracting investment and streamlining project execution.

The rise of power exchanges

As the corporate PPA market faces regulatory and operational challenges, the shift toward power exchanges offers a complementary solution. Power exchanges enhance price discovery, efficiency, and transparency, making them essential tools in India's evolving energy market. According to the Central Electricity Regulatory Commission, the share of power exchanges has grown substantially, with a compound annual growth rate of 16.4% from FY2020 to FY2024.[21] States like Uttarakhand and Himachal Pradesh are leveraging power exchanges to optimize their energy procurement strategies, achieving substantial financial savings and improving operational efficiency.

For instance, Uttarakhand Power Corporation Limited successfully reduced procurement costs by 20% from October 2023 to March 2024 by incorporating market strategies such as the Day-Ahead Market and Real-Time Market on the Indian Energy Exchange.[22] Power exchanges are also playing a crucial role in India's RE transition, signaling a move towards more dynamic, market-driven solutions and away from traditional PPAs.

19. "India's Renewable Energy Open Access Market", Institute for Energy Economics and Financial Analysis, 2022, available at: https://ieefa.org.

20. "Renewable Energy Projects Facing Up to 12-Month Delay in Signing of PPAs", *Economic Times*, 2024, available at: https://energy.economictimes.indiatimes.com.

21. "India's power sector dynamics shift with rising exchange share and declining PPAs", *Economic Times Energy*, 2024, available at: https://energy.economictimes.indiatimes.com.

22. "Power Play: How State Utilities Are Slashing Energy Costs Through Market Strategies", *Economic Times*, 2024, available at: https://energy.economictimes.indiatimes.com.

Rise of virtual power purchase agreements (VPPAs)

In response to the challenges faced by the corporate PPA market, VPPAs are gaining traction as a flexible and innovative financial tool. In this model, a RE generator and a buyer agree on a fixed price for RE, while the generator continues to sell electricity at prevailing market rates. Any market price fluctuations are settled between the parties. This model provides buyers with flexibility, as they can procure electricity from other sources, such as distribution companies or power exchanges.

In September 2023, Cleantech Solar unveiled its first VPPA with a leading FMCG company in India. The project is set to generate approximately 187 GWh of lifetime green energy–equivalent to offsetting over 171 kilotonnes of carbon emissions.[23] As the corporate PPA market continues to evolve, VPPAs offer a promising solution, providing flexibility while contributing to India's growing RE adoption.

Bridging the gaps in India's grid modernization policies

India has made remarkable strides in strengthening its grid infrastructure through initiatives like the National Smart Grid Mission and the Smart Meter National Programme (SMNP). As of January 2025, these efforts have resulted in the deployment of over 20 million smart consumer meters across various schemes.[24]

The SMNP is a key policy aimed at modernizing India's grid. By adopting the Build-Own-Operate-Transfer model, the program encourages private sector participation without requiring upfront financial investment from state governments. However, challenges remain, such as high initial costs and the weak financial health of DISCOMs.

To maximize the potential of grid modernization, India must introduce targeted policies, including long-term financial incentives for emerging technologies such as energy storage and grid automation. Additionally, implementing Locational Marginal Pricing-based dynamic pricing on platforms like the Indian Energy Exchange could enhance energy trading efficiency, improve price signals, and foster a more competitive market.

Addressing remaining barriers requires strengthening Public-Private Partnerships (PPPs), particularly in underserved areas. A matching-grant system, alongside tax incentives, subsidies, and low-interest loans, could encourage private investment and ease financial burdens on states and DISCOMs.

23. "Cleantech Solar Announces the Commercial Operation of Its Maiden Virtual Power Purchase Agreement (VPPA), Amongst the First in India", Cleantech Solar, 2023, available at: https://cleantechsolar.com.

24. "National Smart Grid Mission", National Smart Grid Mission, 2024, available at: www.nsgm.gov.in.

Unlocking private sector investment

Between April 2020 and September 2024, India's RE sector attracted €19.38 billion in Foreign Direct Investment.

Private sector involvement is critical for accelerating the integration of RE into India's grid. Between April 2020 and September 2024, India's RE sector attracted €19.38 billion in Foreign Direct Investment[25], reflecting strong investor confidence.

To further encourage private capital, schemes like the RDSS provide financial support for installing smart meters. The RDSS aims to install 250 million prepaid smart meters by March 2025, prioritizing high-loss areas, Union Territories, and MSMEs. States that meet installation targets receive financial incentives, such as up to ₹1,350 (€15) per meter for Special Category States, with further bonuses for those who meet targets early.[26]

Mitigating risks for private investors

Private investors face challenges such as regulatory uncertainty, shifting policies, and financial constraints. Frequent changes in tariff structures and net metering adjustments can undermine project viability. However, the government's commitment to long-term policy frameworks, exemplified by the Panchamrit Scheme's 500 GW RE target by 2030, signals positive change.

To enhance investor confidence, risk mitigation tools such as Partial Risk Guarantees and first-loss capital mechanisms are essential for ensuring stable returns. Clear, risk-sharing agreements in PPPs can balance risks between the government and investors. By strengthening financial de-risking measures and ensuring policy stability, India can secure long-term private investment, unlocking the full potential of its grid modernization efforts.

25. "Renewable Energy Sector", Invest India, 2024, available at: www.investindia.gov.in.

26. "Press Release: Government Takes Major Steps in Renewable Energy Development", Press Information Bureau, 2023, available at: https://pib.gov.in.

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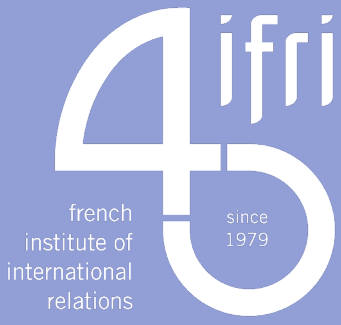

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