

# Grid Integration of Variable Renewable Energy in India: A Review of Technical Challenges, Solutions, and Future Outlook

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## Case Report

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# Grid Integration of Variable Renewable Energy in India: A Review of Technical Challenges, Solutions, and Future Outlook

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## ABSTRACT

India has become one of the fastest-growing solar and wind markets in the world: installed renewable capacity reached about 288.6 GW by 30 June 2026, of which solar alone was 162.2 GW. This growth is changing the way the grid must be planned and operated, because solar and wind are weather-dependent, geographically concentrated and connected through power electronics rather than synchronous machines. This review synthesises peer-reviewed studies, national planning documents and recent (2025–2026) market and system-operator evidence on the technical challenges of integrating variable renewable energy (VRE) into the Indian grid. Five themes are examined: forecasting and scheduling, transmission and geographic balancing, flexibility from thermal plants, hydro, storage and demand, grid stability and inverter control, and market design. The evidence shows that India’s binding constraint has shifted from generation capacity to evacuation and flexibility: roughly 300 GWh of renewable energy was curtailed in the first quarter of 2026 because of transmission limits alone, and more than 50 GW of renewable capacity is reported to be stranded or delayed. Modelling studies indicate that lowering coal minimum-load limits (70% to 40%), wide-area scheduling, better forecasting, storage, and demand response can each cut curtailment, but none is sufficient alone. A qualitative multi-criteria comparison, a four-phase integration roadmap and a set of research gaps are proposed. The review concludes that India can integrate high VRE shares reliably if flexibility adequacy, transmission readiness and market remuneration for system services are planned together with capacity targets.

## 1. Introduction

Electricity demand in India is rising quickly because of economic growth, urbanisation, air-conditioning, industrial expansion and the gradual electrification of transport. At the same time the country has committed to a large share of non-fossil capacity by 2030 and to long-term decarbonisation. Solar photovoltaic (PV) and wind are the main technologies delivering this shift, because their costs have fallen sharply and projects can be built in one to two years. Unlike coal, nuclear or reservoir hydro, however, their output follows sunshine and wind. It can be forecast, but it cannot be commanded, and it changes over seconds, hours, seasons and years [1]–[3].

The scale of the change is now very large. According to MNRE data presented to the Rajya Sabha, installed renewable capacity rose from 76.4 GW in 2014 to 288.6 GW on 30 June 2026, and total non-fossil capacity (including 8.8 GW nuclear) reached 297.4 GW [4]. India added a record 44.6 GW of solar and about 6 GW of wind in FY2026, and a further 26 GW of solar and 2.9 GW of wind in the first half of 2026 alone [5], [6]. Figure 1 and Table 1 summarise the current position.

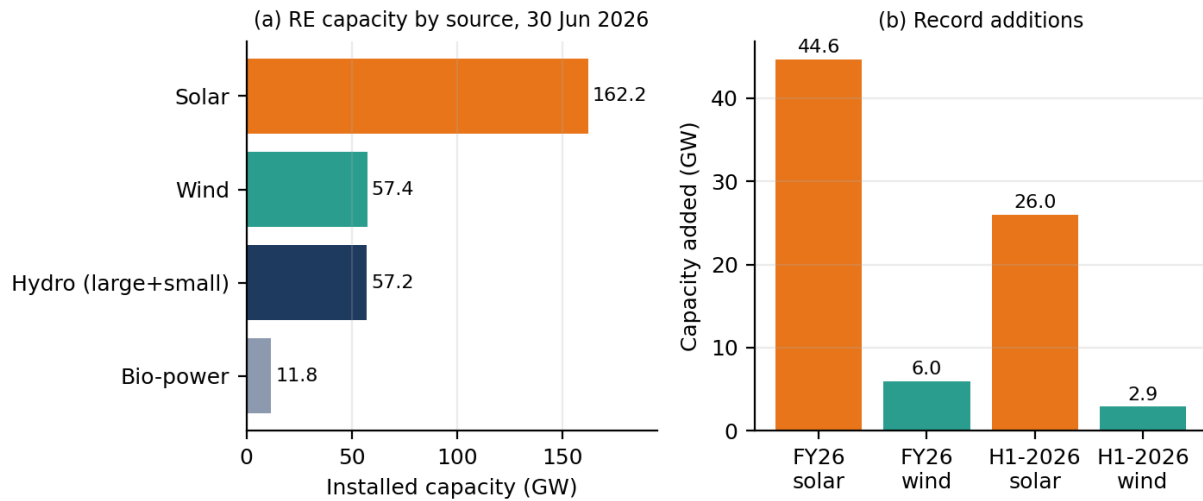


**Fig. 1.** (a) Installed renewable capacity by source at 30 June 2026 (hydro includes small hydro; MNRE data as reported in [4]). (b) Record solar and wind additions in FY2026 and H1 2026 [5], [6].

**Table 1.** Snapshot of India's renewable build-out and grid-integration indicators (2026).

| Indicator                           | Value                                                | Source                  |
|-------------------------------------|------------------------------------------------------|-------------------------|
| Installed RE capacity (30 Jun 2026) | 288.6 GW                                             | MNRE via [4]            |
| Solar / wind capacity               | 162.2 GW / 57.4 GW                                   | MNRE via [4]            |
| Non-fossil capacity incl. nuclear   | 297.4 GW                                             | MNRE via [4]            |
| Solar added, FY2026                 | 44.6 GW (ground-mounted 34.8 GW; rooftop 8.7 GW)     | JMK Research [5]        |
| Solar + wind added, H1 2026         | ≈ 29 GW (record)                                     | JMK Research [6]        |
| RE curtailed on ISTS, Q1 2026       | 470 GWh, of which ≈ 300 GWh from transmission limits | Ember [7]               |
| RE stranded or delayed (mid-2025)   | > 50 GW (Rajasthan ≈ 8 GW)                           | IEEFA & JMK [8]         |
| Operational BESS (Aug 2026)         | 9.08 GWh (vs. 34.72 GWh needed in FY2026-27)         | Rubix Data Sciences [9] |

These numbers show that renewable integration is no longer only a question of building more generation. A useful distinction is between **capacity adequacy**, which asks whether enough installed megawatts exist to meet peak demand, and **flexibility adequacy**, which asks whether those megawatts can change output quickly, at the right place and for long enough when net demand changes. Das *et al.* show that Indian planning has historically under-represented the second question [1]. A system can have enough capacity on paper and still curtail clean energy, violate frequency limits or pay high balancing costs.

**Objectives and scope.** This paper (i) explains the physical basis of the VRE-integration problem, (ii) reviews and compares the solutions reported in the literature and in recent Indian system data, (iii) presents analysis charts and a qualitative comparison of options, and (iv) proposes a staged roadmap and research gaps. The review covers peer-reviewed articles, national studies (NREL/LBNL, IEA, IRENA, CEA, MNRE) and 2025–2026 market reports. Because the Indian situation is changing monthly, recent figures from press and think-tank reports are used only for current-status indicators and are labelled as such.

## 2. Fundamentals and theoretical background

### 2.1 Power balance, net load and the duck curve

At every instant the grid must satisfy the power balance, in which generation, storage discharge and imports equal load, storage charging, exports and losses:

$$\sum P_{g,i}(t) + P_{dis}(t) + P_{imp}(t) = P_L(t) + P_{ch}(t) + P_{exp}(t) + P_{loss}(t) \quad (1)$$

Solar and wind enter this balance as time-varying injections that the operator cannot dispatch freely. The operator therefore schedules controllable plants against the **net load**:

$$P_{net}(t) = P_L(t) - P_{VRE}(t) \quad (2)$$

When solar is strong at midday and falls quickly after sunset, net load has a deep belly and a steep evening rise – the “duck curve”. Figure 2 shows an illustrative Indian-style daily profile that was constructed for this review (not measured data). In this example net load falls to about 89 GW at 11:15 and climbs to about 181 GW by 20:30. The largest three-hour net-load ramp is about 54 GW, more than twice the 25 GW ramp of the underlying demand without VRE. The relevant operating requirement is therefore the ramp and the minimum-load margin, not only the evening peak.

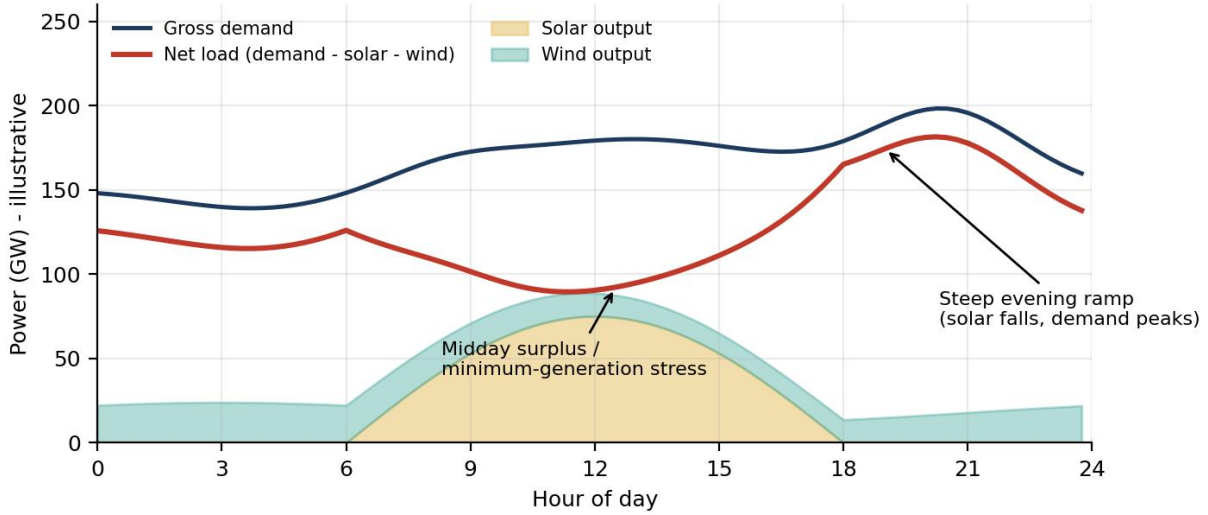


**Fig. 2.** Illustrative daily gross demand, solar and wind output, and resulting net load (author’s constructed profile to explain the duck-curve concept; values are indicative).

## 2.2 Flexibility and reserve requirement

Flexibility is multi-dimensional: a resource must offer sufficient operating range, ramp rate, response time, energy duration and availability. Fast frequency reserves arrest a disturbance within seconds, restoration reserves bring frequency back, and replacement reserves hold the balance for longer. Batteries respond almost instantly but are limited by stored energy; reservoir and pumped hydro combine fast ramping with hours of energy but depend on site and water; coal units hold large energy but are constrained by minimum stable load, ramp rate and start-up time [1], [10]. A simplified ramp-reserve requirement over an interval  $\Delta t$  is

$$R_{req}(t) = |\Delta P_L(t) - \Delta P_{VRE}(t)| + R_{cont} \quad (3)$$

where  $R_{cont}$  is the contingency reserve. Forecast uncertainty adds a probabilistic term, so planners should size reserves for high-percentile ramps and renewable “drought” periods, not for the expected value only. Sub-hourly chronological production-cost models are needed for this purpose; annual energy-balance models are not sufficient [1], [2], [11].

## 2.3 Frequency, voltage and inverter-based resources

Synchronous generators store rotational energy that slows the initial rate of change of frequency after a disturbance. Solar PV and most wind plants are connected through converters and give no natural inertia [12]. They can, however, provide synthetic inertia, fast frequency response, reactive power and curtailment on command if headroom, controls, communications and grid-code requirements are in place [10], [13]. At high penetration, “system strength” (the ability of the grid to hold voltage and support converter control) becomes as important as inertia, and weak-grid interactions can affect protection and stability [10].

At distribution level, rooftop PV can cause reverse power flow, local over-voltage, transformer and feeder loading, and protection mis-coordination. India added 8.7 GW of rooftop solar in FY2026 and 6.4 GW in H1 2026 alone, driven largely by the PM Surya Ghar scheme [5], [6], so these effects are becoming practical rather than theoretical. Smart inverters can regulate reactive and active power, but only if functions are standardised and visible to the distribution utility [3], [13].

## 2.4 Curtailment and its economics

Curtailment is the reduction of available renewable output because of congestion, minimum-generation limits, insufficient demand, reserve needs, stability limits or contractual rules. A simple curtailment ratio is

$$C_{VRE} = (E_{avail} - E_{deliv}) / E_{avail} \times 100 \% \quad (4)$$

Zero curtailment is not the economic objective. Building wires or storage to save every last megawatt-hour can cost more than the energy saved, so the goal is minimum total system cost subject to reliability and emissions limits [11]. The question for India is whether the present curtailment is the efficient kind (rare, short, at the margin) or the structural kind (daily, concentrated at a few nodes, caused by delayed infrastructure). The 2026 evidence in Section 3.2 suggests the latter at several nodes.

## 3. Literature review and analysis

### 3.1 Review method and key studies

Sources were selected for relevance to VRE integration in India or to technologies directly applicable to it, and were grouped into five themes. Table 2 lists the principal studies used for the technical conclusions; recent market data are cited separately where used.

**Table 2.** Principal studies reviewed and their main contribution.

| Study                                                                | Scope                                                                             | Main contribution (as reported)                                                                                                                                                                  | Theme                   |
|----------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
| Palchak <i>et al.</i> (2017) [2]                                     | <i>Greening the Grid</i> – NREL/LBNL production-cost study of 175 GW RE for India | Balancing 100 GW solar + 60 GW wind judged technically feasible at 15-min scale; curtailment $\approx$ 1.4% in the base 2022 case; wider-area scheduling and lower coal minimum load matter most | Scheduling, flexibility |
| Das <i>et al.</i> (2020) [1]                                         | Flexibility requirement for large-scale RE in India                               | Defines flexibility by range, ramp and duration; shows planning must link capacity expansion with operations                                                                                     | Planning                |
| IEA (2021) [3]                                                       | <i>Renewables Integration in India</i>                                            | State-level analysis; real-time markets, demand response and rooftop-PV connection rules; long-term physical PPAs as a barrier                                                                   | Markets, policy         |
| CEA (2023) [14]                                                      | Transmission plan for > 500 GW non-fossil by 2030                                 | Corridors, reactive support and interstate system needed to evacuate renewable zones                                                                                                             | Transmission            |
| Denholm & Hand (2011) [11]                                           | Very high VRE penetration, Texas                                                  | Flexibility and storage needs rise non-linearly at high penetration; curtailment trade-offs                                                                                                      | Fundamentals            |
| Kroposki <i>et al.</i> (2017) [10]                                   | Operating grids at very high VRE                                                  | Inverter controls, grid-forming capability and system strength are central                                                                                                                       | Stability               |
| Shafiullah <i>et al.</i> (2022) [13]; Alam <i>et al.</i> (2020) [12] | Reviews of PV / high-VRE grid impacts                                             | Voltage, frequency, harmonic and protection issues with mitigation options                                                                                                                       | Stability, distribution |
| Zakeri & Syri (2015) [15]                                            | Life-cycle cost of storage                                                        | Bulk storage such as pumped hydro is cost-effective; batteries suit short-duration, fast services                                                                                                | Storage                 |
| Ember (2026) [7]; IEEFA & JMK (2025) [8]                             | Curtailment and stranded capacity                                                 | Transmission is now a binding constraint; over 50 GW stranded or delayed                                                                                                                         | Transmission            |

### 3.2 Transmission, congestion and curtailment: the 2026 evidence

India's best solar and wind resources lie in Rajasthan, Gujarat, Karnataka, Tamil Nadu and Maharashtra, while load is spread across the country. Transmission therefore has two roles: it carries energy from resource zones to demand centres, and it pools weather diversity. The CEA plan for evacuating more than 500 GW of non-fossil capacity by 2030 is the principal response [14]. The difficulty is timing. Renewable projects take one to two years to build, whereas lines face right-of-way, forest-clearance and equipment delays, and India has met only about 80% of recent transmission targets [7].

The consequences are now visible in system data. Ember reports that 470 GWh of renewable energy was curtailed on the interstate system between January and March 2026, of which about 300 GWh (nearly two-thirds) was due to transmission constraints; on 30 March 2026 alone about 34 GWh was lost [7]. At the time, 43.7 GW of solar and 12.5 GW of wind were connected to the interstate network [7]. In Rajasthan, grid-operator data cited in the trade press show about 23 GW of commissioned renewable capacity against about 18.9 GW of transmission capacity, and roughly 4.3 GW of solar facing near-complete curtailment during daytime [16]. Commissioning of the 765 kV Khetri–Narela line enabled connectivity for about 4.8 GW of additional capacity, but risks remained [17]. An IEEFA–JMK study estimated that more than 50 GW of renewable capacity was stranded across India as of June 2025, about 8 GW of it in Rajasthan [8]. Industry associations also reported average curtailment of 15–20% in major RE states over the preceding year, with midday peaks reaching 100% at some plants [18]; these figures are industry-reported and should be treated as indicative until confirmed by system-operator statistics.

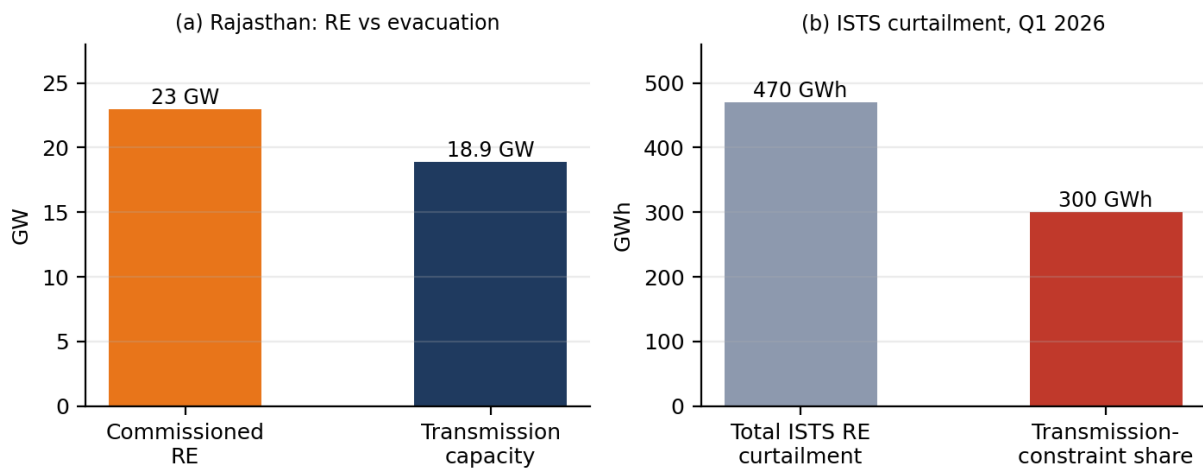


**Fig. 3.** (a) Rajasthan commissioned renewable capacity versus transmission capacity [16]. (b) Interstate-system RE curtailment in Q1 2026 and the share attributed to transmission constraints [7].

Two lessons follow. First, national averages hide local stress: curtailment concentrates at a few pooling stations during midday. Second, simply adding corridors is not enough, because lines are used for only a few high-output hours. Storage at pooling stations, dynamic line rating, transformer augmentation and connectivity rules that avoid reserving capacity for stalled projects can raise utilisation of the wires already built [8], [19]. Integrated generation–transmission planning, published hosting-capacity maps and curtailment-risk disclosure would improve project finance and reduce over-building at congested nodes.

### 3.3 Forecasting and operational scheduling

Forecasting is the lowest-cost form of flexibility because it reduces uncertainty before any physical resource is committed. Solar forecasts use irradiance, cloud motion, temperature and plant telemetry; wind forecasts use numerical weather prediction, turbine data and ensembles. Data-driven methods can improve short-horizon accuracy, but benefits depend on data quality, regime change and integration into control-room workflows. Accuracy should be assessed at the resolution used for scheduling (for example 15-minute blocks), not only for daily energy.

Aggregation matters strongly in India. *Greening the Grid* used actual and forecast wind and solar data in a production-cost model and found that balancing 100 GW of solar and 60 GW of wind was technically feasible at 15-minute resolution, with annual curtailment of about 1.4% in the base case [2]. It also found that scheduling over a wider balancing area gave larger savings than faster thermal ramp rates. The IEA likewise highlights real-time markets as a way to correct forecast error closer to delivery [3]. Where most energy is locked in inflexible long-term contracts, however, better forecasts cannot be turned into dispatch flexibility. Probabilistic forecasts that feed automatic reserve sizing and congestion management would be more useful to Indian control rooms than a single deterministic number.

### 3.4 Flexibility from conventional plants, hydro, storage and demand

#### 3.4.1 Coal-fleet flexibility

Coal will remain the backbone of reliability in the near term, so making selected units more flexible is the fastest route to extra headroom. In the *Greening the Grid* scenario, lowering the minimum stable generation of coal units from 70% to 40% reduced modelled curtailment from 3.5% to 0.76% (Fig. 4a), and this lever was more powerful than a modest rise in ramp rate [2]. The ability to turn down creates room for midday solar. Flexibility has costs, namely thermal stress, higher heat rate, maintenance and emissions per unit of energy, so a plant-by-plant assessment is needed to protect efficient units and to compare retrofits with storage and demand response on a system-cost basis.

#### 3.4.2 Hydro and pumped storage

Hydro and pumped storage supply ramping, reserves and multi-hour shifting. India had 7.4 GW of pumped-storage capacity in operation at June 2026 [20], and the competitive pumped-hydro pipeline was reported to have grown to 132 GWh from 50 GWh in 2024 [21]. Pumped storage has long lead times, geological and environmental approvals and high capital cost, but its long duration complements batteries.

#### 3.4.3 Battery energy storage

The CEA's National Electricity Plan projects storage needs of 82.37 GWh in 2026-27 rising to 411.4 GWh in 2031-32 (74 GW), comprising 236.22 GWh of batteries and 175.18 GWh of pumped hydro [9], [22] (Fig. 4b). The more recent National Generation Adequacy Plan projects 174 GW / 888 GWh of storage by 2035-36, including about 80 GW / 321 GWh of batteries [23]. Actual deployment is catching up quickly but from a very small base: operating BESS rose from 0.78 GWh in December 2025 to 8.7 GWh in the first half of 2026, about 70% of it merchant projects [24].

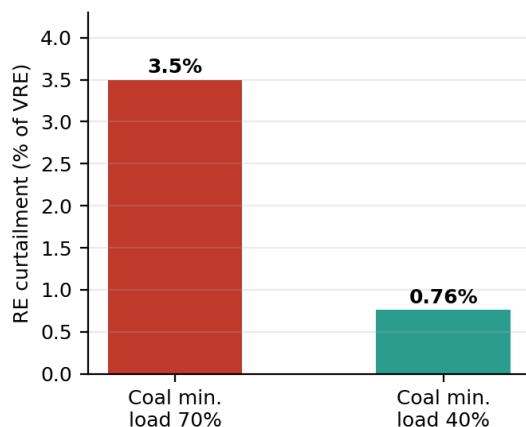


**Fig. 4a.** Effect of coal minimum load on modelled curtailment [2].

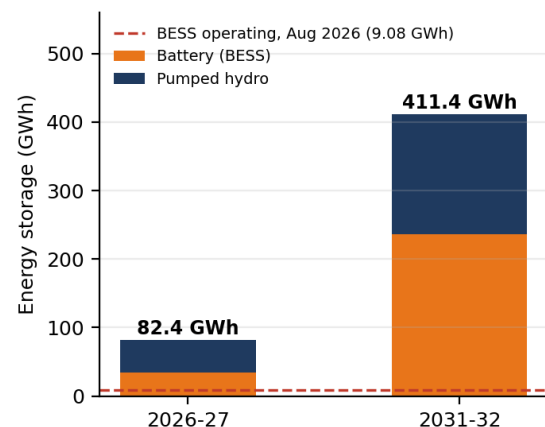


**Fig. 4b.** CEA storage requirement by technology [9], [22]; operating BESS at Aug 2026 shown for comparison.

The pipeline is large but the delivery gap is the real risk. As of August 2026, 9.08 GWh of BESS was operational, 79.92 GWh under construction, 24.13 GWh awarded and 63.53 GWh under tendering, a total of 176.66 GWh or about 75% of the 2031-32 battery requirement (Fig. 5) [9]. Rubix also notes that of the 28 GW tendered in H1 2026 only about 9 GW was auctioned [9]. Policy support includes a second Viability

Gap Funding tranche of ₹5,400 crore for 30 GWh of standalone BESS with 20% domestic value addition, following a first 4 GWh scheme in 2023 [21], and Rajasthan’s requirement of 5% storage for renewable projects above 5 MW [21]. Value is highest when batteries are co-optimised across energy, reserve and congestion-relief services rather than only daily shifting; contracts should reward availability, response performance and state-of-charge management. Degradation, temperature, safety and supply-chain exposure must be included in economics [15].

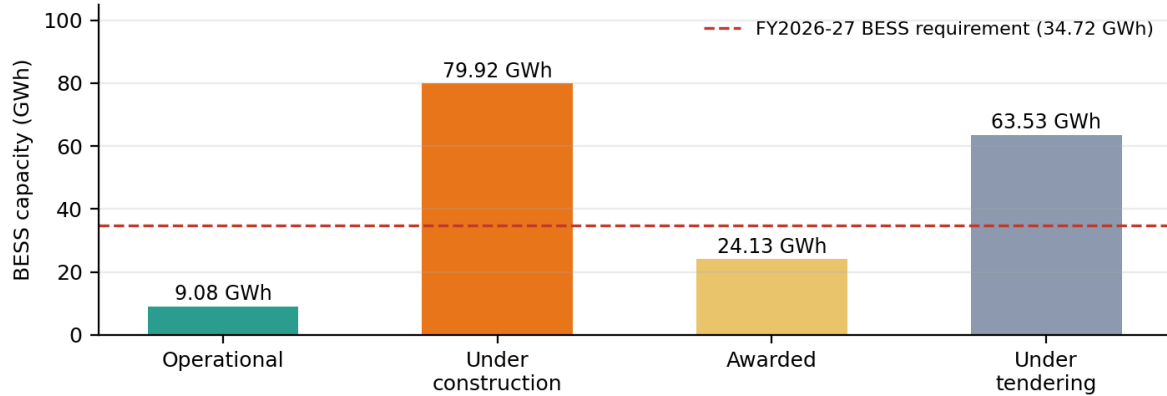


**Fig. 5.** India’s BESS pipeline by stage compared with the FY2026-27 requirement, August 2026 [9].

### 3.4.4 Demand response and electrification loads

Demand response uses flexibility that already exists. Agricultural pumping, industrial processes, cold storage, water supply, commercial cooling and electric-vehicle charging can move load away from high net-load periods. The IEA identifies agricultural load shifting as an important existing resource and recommends a move from involuntary shifting to price-responsive programmes, while noting water-stress risks [3]. Time-of-use tariffs, advanced metering and aggregators are required, and performance must be settled against a credible baseline. GRID-India has observed demand swings of up to 90 GW, which underlines the value of such flexibility [25].

### 3.5 Stability, power quality and grid codes

As synchronous generation is displaced during high-VRE hours, the system needs new sources of fast frequency response and voltage support. Options include batteries, curtailed-renewable headroom, hydro governors, demand response and modified inverter controls; none dominates across all time scales, so reserve products should specify activation time, duration, accuracy and recovery [10], [12], [13]. Grid-forming inverters and synchronous condensers may be needed where short-circuit strength is low. Renewable plants should ride through voltage and frequency disturbances, supply reactive current and follow set-points, and compliance should be tested at commissioning and monitored in operation because control settings can drift after software changes.

Distribution networks need a parallel transition. Hosting-capacity analysis, volt/VAR control, dynamic protection and feeder automation raise rooftop-PV absorption, but digitalisation adds cyber-security and interoperability risks. Open standards, role-based access, logging and fall-back modes should be treated as reliability infrastructure rather than optional features.

### 3.6 Market design and regulation

Technical solutions fail if market rules do not value them. The IEA reports that physical long-term power-purchase agreements cover the large majority of Indian generation (roughly 90–95%), which limits flexible trade and plant operation [3]. Reform need not remove long-term contracts: it can separate capacity adequacy from energy dispatch, allow financial contracting and give transparent short-term access to flexibility. Ancillary-service markets should pay for frequency response, reserves, ramping, reactive power and black-start capability, and co-optimising energy and reserves reduces inefficient commitment. Firm and time-shaped renewable products (for example solar-plus-storage and firm-and-dispatchable tenders) align

procurement with operational value better than nameplate tenders. The financial health of distribution companies must also improve, because payment delay discourages participation by flexible resources.

Planning models should move from annual energy accounting to chronological, multi-area, probabilistic analysis that includes sub-hourly VRE profiles, forecast error, unit commitment, minimum loading, transmission outages, storage state-of-charge and extreme weather [1]. Table 3 summarises the integration measures and their limitations.

**Table 3.** Integration measures, problems addressed and limitations.

| Measure                        | Main problem addressed                          | Time scale         | Important limitation                                 |
|--------------------------------|-------------------------------------------------|--------------------|------------------------------------------------------|
| Probabilistic VRE forecasting  | Forecast error; reserve sizing                  | Minutes–days       | Needs high-quality plant and weather data            |
| Wide-area scheduling           | Geographic mismatch; curtailment                | Minutes–seasons    | Needs transmission and market coordination           |
| Coal-unit flexibility retrofit | Minimum generation; net-load ramps              | Minutes–hours      | Cycling cost and emissions penalty                   |
| Hydro and pumped storage       | Multi-hour shifting; reserves                   | Hours–days         | Site, water and approval constraints; long lead time |
| Battery storage                | Fast response; peak shifting; congestion relief | Seconds–hours      | Degradation, safety, duration, supply chain          |
| Demand response                | Peak demand and ramping                         | Minutes–days       | Participation, baseline uncertainty, water stress    |
| Smart inverters / grid codes   | Voltage, frequency, ride-through                | Cycles–minutes     | Standards, testing, communications                   |
| Transmission + DLR             | Congestion; geographic diversity                | Real time–years    | Right-of-way, delays; low utilisation if mis-sited   |
| Ancillary-service markets      | Unpaid flexibility                              | Real time–planning | Liquidity; settlement complexity                     |

#### 4. Comparative analysis of integration options

To make the literature comparable, the main options were scored on five criteria using a 1–5 scale (5 = most favourable): speed of deployment, response speed, energy duration, cost and effectiveness in relieving curtailment. The scores in Fig. 6 are the author’s qualitative judgement derived from the evidence in Section 3 and are meant to show relative strengths, not to replace system studies.

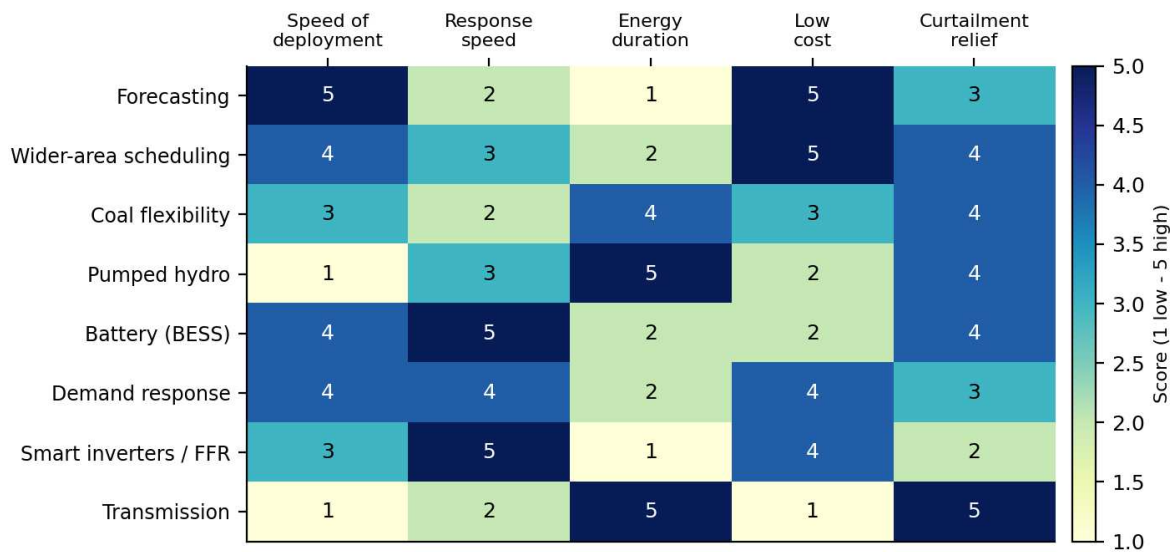


**Fig. 6.** Qualitative multi-criteria comparison of VRE-integration options for India (author’s synthesis of [1]–[3], [9], [10], [15]; not measured data).

Three observations emerge. Forecasting and wide-area scheduling score highest on speed and cost but cannot supply energy or physical response, so they enable rather than replace hardware. Batteries are strong on response and deployment speed but weaker on duration, which is why pumped hydro and demand response remain necessary; transmission is the most effective single curtailment remedy but the slowest and costliest. The pattern supports a portfolio approach: quick, cheap operational measures first, then storage and wires at identified bottlenecks, with market reform running in parallel.

## 5. Applications in the Indian energy sector

### 5.1 Renewable-rich states and green-energy corridors

Rajasthan and Gujarat lead solar additions (in FY2026 they accounted for 35% and 26% of utility-scale additions respectively) [5], while Karnataka, Tamil Nadu and Maharashtra contribute large wind and hybrid portfolios. Their needs differ: solar-heavy systems face midday surplus and evening ramps, wind-heavy systems face seasonal variability, and mixed portfolios benefit from complementarity. State load-dispatch centres should use sub-hourly forecasts, reserve dashboards and coordinated interstate schedules, and corridors should be planned together with storage and reactive-power assets [14].

### 5.2 Renewable-plus-storage and firm renewable projects

Solar–wind–storage hybrids and firm-and-dispatchable renewable energy projects can offer shaped delivery profiles, firm capacity in selected hours and better utilisation of lines. Examples reported in 2026 include multi-GWh storage at the Khavda park in Gujarat and about 1 GWh of storage at Rajasthan solar projects [26]. Such projects should be evaluated on delivered energy, capacity contribution, reserve performance, degradation and curtailment, not only on nameplate capacity.

### 5.3 Industrial and chemical-process loads

Chemical, fertiliser, steel, cement and refining industries combine flexible loads (electrolysers, compressors, pumps, chillers, some batch processes) with loads needing firm supply. Coupling renewable electricity with thermal storage, green-hydrogen production or flexible auxiliary systems can raise renewable absorption without harming product quality. Automated, price-linked industrial demand response is most valuable, provided contracts define production limits and recovery periods.

### 5.4 Rooftop solar, electric mobility and distribution systems

Rooftop PV reduces daytime feeder load but can create reverse flow and a sharper evening peak. Smart inverters, behind-the-meter batteries and time-of-use tariffs convert these assets into grid resources, and managed EV charging adds flexible load; uncontrolled charging would instead deepen evening peaks. Distribution utilities need feeder-level hosting-capacity maps, interoperable meters and consumer incentives before such resources can be relied on [3], [13].

### 5.5 Mini-grids and resilience

Solar–battery mini-grids with backup generation improve reliability in weak-grid and remote areas and reduce diesel use. Their controllers must hold voltage and frequency in both islanded and grid-connected modes. The same metering, communication and cyber-security foundations support both local access and bulk-system integration.

## 6. Challenges and limitations

**Table 4.** Principal challenges, evidence from India, and the corresponding mitigation.

| Challenge             | Evidence / impact                                                                           | Mitigation                                                                 |
|-----------------------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Infrastructure timing | ≈ 300 GWh transmission-related curtailment in Q1 2026; > 50 GW stranded or delayed [7], [8] | Integrated generation–transmission planning; DLR; BESS at pooling stations |
| Flexibility shortfall | Duck-curve ramps; coal minimum load of 70% blocks midday solar [2]                          | Coal retrofits to 40%; hydro/PSP; demand response                          |

| Challenge                | Evidence / impact                                       | Mitigation                                                  |
|--------------------------|---------------------------------------------------------|-------------------------------------------------------------|
| Storage delivery gap     | 9.08 GWh operating vs 34.72 GWh needed in FY2026-27 [9] | Faster auctions, VGF, standard contracts, safety regulation |
| Contracts and markets    | Physical PPAs $\approx$ 90–95% of generation [3]        | Financial contracts, real-time and ancillary markets        |
| Inverter-dominated grid  | Reduced inertia and system strength [10], [12]          | Grid-forming inverters, FFR products, strict code testing   |
| Distribution readiness   | Rooftop PV 8.7 GW in FY2026 [5]; poor visibility        | Hosting capacity, smart inverters, AMI, cyber-security      |
| Data and models          | Limited public sub-hourly datasets; few weather years   | Open benchmark datasets; extreme-event scenarios            |
| Institutions and finance | State vs national optimisation; DISCOM payment risk     | Coordinated dispatch; payment security; transparent rules   |

Several limitations of the evidence should be noted. Many modelling studies, including *Greening the Grid*, rely on a limited number of historical weather years and may understate compound events such as heat waves with low wind, prolonged monsoon cloud, dust storms or simultaneous transmission outages. International grid-code experience cannot be copied directly because India's topology, generation mix and institutions differ. Recent curtailment and storage statistics come partly from press and think-tank summaries and may be revised as official data are published. All results should therefore be read as scenario-dependent rather than guaranteed.

## 7. Integration roadmap and research gaps

### 7.1 Proposed four-phase roadmap

Combining the evidence, a staged pathway is proposed (Fig. 7). Phase 1 improves visibility, because operators cannot manage what they cannot see: probabilistic forecasting, plant telemetry and a registry of rooftop PV. Phase 2 unlocks flexibility that already exists: lower coal minimum loads, wide-area scheduling and verified grid-code compliance. Phase 3 builds physical assets at the bottlenecks: storage and reactive support at renewable pooling stations, pumped hydro and corridors. Phase 4 reforms markets so that ramping, reserves, reactive power and fast frequency response are paid. The phases overlap, but the order reflects cost and speed.

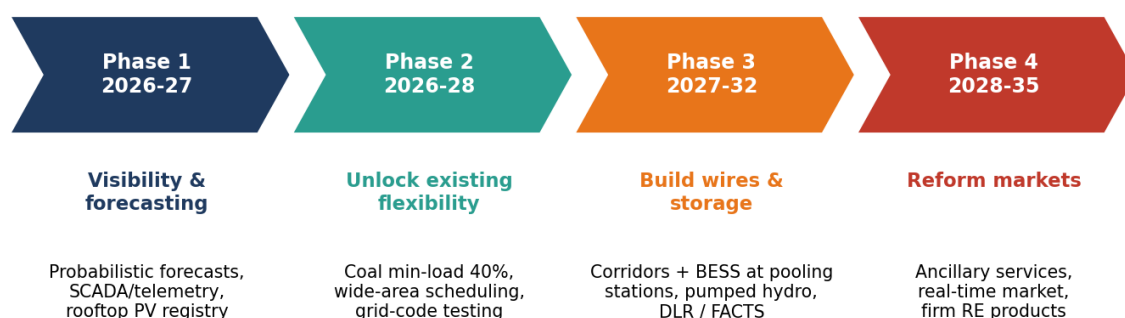


Fig. 7. Proposed staged pathway for integrating high VRE shares in India (author's synthesis).

### 7.2 Research gaps and future directions

- **Open data:** India-specific sub-hourly datasets linking plant output, weather, load, transmission status and curtailment, with public benchmarks for forecasting and optimisation methods.
- **Integrated flexibility planning:** common nodal, chronological frameworks that quantify the marginal value of one more MW or MWh of each option (storage, transmission, coal retrofit, demand response) at specific renewable nodes.

- **Extreme-event robustness:** models of renewable droughts, heat waves, monsoon variability and simultaneous outages rather than average weather years.
- **Market design:** products and settlement for ramping, reserves, reactive power and fast frequency response that protect consumers from excess volatility.
- **Grid-forming technology:** field trials of grid-forming inverters, synchronous condensers and weak-grid performance in Rajasthan and Gujarat-type nodes.
- **Distribution and EVs:** links between rooftop PV, managed EV charging, aggregators and transmission planning, with interoperable and secure communication.
- **Socio-economic effects:** land, water, employment and affordability; for example agricultural demand response must not worsen groundwater stress.
- **Field evidence:** measured performance of renewable-plus-storage projects, flexible coal operation and ancillary-service pilots to complement model results.

## 8. Conclusions

India's renewable-integration challenge has moved from a question of how fast capacity can be added to a question of how well the system can absorb it. With 288.6 GW of renewable capacity installed by June 2026 and record annual additions, the limiting factors are now evacuation capacity, operating flexibility and market remuneration. Transmission-related curtailment of about 300 GWh in a single quarter, more than 50 GW of capacity reported stranded or delayed, and 9 GWh of operating battery capacity against a requirement several times larger show that the gap between plans and delivery is the key risk.

The literature supports a portfolio approach. Near-term measures with the highest value for cost are better forecasting, wide-area and sub-hourly scheduling, lower coal minimum loads, and use of existing demand flexibility. Medium-term measures are storage and reactive support at congested pooling stations and long-duration pumped hydro. Smart inverters, grid-code enforcement and distribution visibility must advance together, and market reforms must pay flexibility providers for the services they deliver. The central policy implication is that renewable capacity targets should be accompanied by measurable flexibility and deliverability targets, such as forecast accuracy, reserve availability, ramping capability, hosting capacity, storage duration, curtailment and response performance. If these steps are implemented in a coordinated sequence, India can continue to raise its renewable share while maintaining reliability, affordability and decarbonisation progress.

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## Declaration of competing interest

The author declares that there are no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

## References

- [1] P. Das, P. Mathuria, R. Bhakar, J. Mathur, A. Kanudia, and A. Singh, "Flexibility requirement for large-scale renewable energy integration in Indian power system: Technology, policy and modeling options," *Energy Strategy Reviews*, vol. 29, p. 100482, 2020. doi:10.1016/j.esr.2020.100482
- [2] D. Palchak *et al.*, *Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I – National Study*. Berkeley, CA / Golden, CO, USA: Lawrence Berkeley National Laboratory and National Renewable Energy Laboratory, 2017.
- [3] International Energy Agency, *Renewables Integration in India*. Paris, France: IEA, 2021. [Online]. Available: <https://www.iea.org/reports/renewables-integration-in-india>
- [4] Energetica India, "India's renewable energy capacity reaches 288.58 GW as of June 2026: Shripad Yesso Naik" (reply to Rajya Sabha question, MNRE), 22 Jul. 2026. [Online]. Available: <https://www.energetica-india.net/news/>

- [5] JMK Research, “India installs record 44 GW solar and 6 GW wind capacity in FY2026,” 2026. [Online]. Available: <https://jmkresearch.com/india-installs-record-44-gw-solar-and-6-gw-wind-capacity-in-fy2026/>
- [6] JMK Research, “India installs record 26 GW solar and 3 GW wind capacity in H1 2026,” 2026. [Online]. Available: <https://jmkresearch.com/india-installs-record-26-gw-solar-and-3-gw-wind-capacity-in-h12026/>
- [7] Ember, “Transmission gaps are beginning to constrain India’s rapid renewables integration,” 2026 (reported in *Down To Earth*, “India loses 300 GWh renewable energy in 2026 first quarter due to transmission delays”).
- [8] IEEFA South Asia and JMK Research, report on stranded renewable capacity and transmission constraints in India, Sept. 2025 (reported in *PV Tech*, 24 Sept. 2025).
- [9] Rubix Data Sciences, “India’s battery energy storage system requirement to rise nearly seven-fold to 236 GWh by FY2031-32,” *pvmagazine India*, 7 Oct. 2026.
- [10] B. Kroposki *et al.*, “Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy,” *IEEE Power and Energy Magazine*, vol. 15, no. 2, pp. 61–73, 2017.
- [11] P. Denholm and M. Hand, “Grid flexibility and storage required to achieve very high penetration of variable renewable electricity,” *Energy Policy*, vol. 39, no. 3, pp. 1817–1830, 2011.
- [12] M. S. Alam *et al.*, “High-level penetration of renewable energy sources into grid utility: Challenges and solutions,” *IEEE Access*, vol. 8, 2020.
- [13] M. Shafiullah *et al.*, “Grid integration challenges and solution strategies for solar PV systems: A review,” *IEEE Access*, vol. 10, 2022.
- [14] Central Electricity Authority, *Transmission System for Integration of over 500 GW Non-fossil Capacity by 2030*. New Delhi, India: CEA, 2023.
- [15] B. Zakeri and S. Syri, “Electrical energy storage systems: A comparative life cycle cost analysis,” *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 569–596, 2015.
- [16] Outlook Business, “Nearly 4 GW of solar capacity in Rajasthan hit by transmission constraints,” 2026 (citing NRLDC data).
- [17] Outlook Business, “Rajasthan’s renewable projects face peak-hour shutdowns despite new transmission line,” 1 May 2026.
- [18] The Core, “India’s green energy boom faces a costly hurdle as lagging power lines and grid congestion force massive wastage,” 3 Mar. 2026.
- [19] Powerline, “Transmission imperative: Integrated planning for grid and renewables expansion key to reducing curtailment,” 4 Sept. 2026.
- [20] Energetica India, “India installs 13.9 GW renewable energy capacity in Q1 FY27, solar reaches 162 GW,” 2026.
- [21] SolarQuarter, “India’s energy storage sector set for major breakout in 2026: IESA,” 7 Jan. 2026.
- [22] Energy-Storage.news, “Mercom: 90% of India’s 219 MWh BESS fleet is paired with solar PV generation,” 2024 (citing CEA National Electricity Plan).
- [23] TaiyangNews, “POWERGRID invites bids for 750 MW/2,000 MWh BESS,” July 2026 (citing CEA projections to 2035-36).
- [24] India Energy Storage Alliance and Customized Energy Solutions, *India BESS Market Review*, 2026 (reported by IBEF, July 2026).
- [25] SolarQuarter, “102 GWh tender boom powers India’s energy storage growth to 346 GWh by 2033,” 20 Mar. 2026.
- [26] Renewable Watch, “Growing pipeline: Battery storage market moves towards larger-scale deployment,” 30 Jun. 2026.